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Scalable Wireless Sensor Networks for Dynamic Communication Environments: Simulation and Modelling

by

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ABSTRACT

FACULTY OF ENGINEERING, SCIENCE AND MATHEMATICS
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This thesis explores the deployment of Wireless Sensor Networks (WSNs) on localised maritime events. In particular, it will focus on the deployment of a WSN at sea and estimating what challenges derive from the environment and how they affect communication. This research addresses these challenges through simulation and modelling of communication and environment, evaluating the implications of hardware selection and custom algorithm development.

The first part of this thesis consists of the analysis of aspects related to the Medium Access Control layer of the network stack in large-scale networks. These details are commonly hidden from upper layers, thus resulting in misconceptions of real deployment characteristics. Results show that simple solutions have greater advantages when the number of nodes withing a cluster increases.

The second part considers routing techniques, with focus on energy management and packet delivery. It is shown that, under certain conditions, relaying data can increase energy savings, while at the same time allows a more even distribution of its usage between nodes.

The third part describes the development of a custom-made network simulator. It starts by considering realistic radio, channel and interference models to allow a trustworthy simulation of the deployment environment. The MAC and Routing techniques developed thus far are adapted to the simulator in a cross-layer manner.

The fourth part consists of adapting the WSN behaviour to the variable weather and topology found in the chosen application scenario. By analysing the algorithms presented in this work, it is possible to find and use the best alternative under any set of environmental conditions. This mechanism, the environment-aware engine, uses both network and sensing data to optimise performance through a set of rules that involve message delivery and distance between origin and cluster head.

Contents

Acknowledgements **xix**

1 Introduction **1**
1.1 Wireless sensor networks . . . 1
1.2 Case scenario . . . 5
1.2.1 WSNs for localised maritime monitoring . . . 5
1.2.2 Ocean surface waves . . . 6
1.2.3 Deployment of sensor networks at sea . . . 8
1.3 Research contribution . . . 8
1.3.1 Justification and motivation . . . 9
1.3.2 Aims . . . 10
1.3.3 Scope and challenges . . . 11
1.3.4 Contributions . . . 12
1.4 Thesis structure . . . 13
1.5 Publications . . . 14

2 Wireless Sensor Networks **17**
2.1 Overview of sensor networks . . . 17
2.1.1 Application-driven development . . . 19
2.2 Network . . . 20
2.2.1 Energy . . . 21
2.2.2 Energy depletion rate . . . 23
2.2.3 Connectivity . . . 25
2.2.4 Latency . . . 25
2.2.5 Cross-layer optimisation . . . 26
2.2.6 IEEE 802.15.4 . . . 26
2.2.7 ZigBee . . . 27
2.2.8 6LowPAN . . . 27
2.2.9 Bluetooth Low Energy . . . 28
2.3 Medium Access Control . . . 29
2.3.1 Random assignment protocols . . . 30
2.3.2 Fixed assignment protocols . . . 33
2.3.3 On-demand assignment protocols . . . 33
2.4 Routing algorithms and protocols . . . 33
2.4.1 Protocols division . . . 34
2.4.2 Flat protocols . . . 35
2.4.3 Hierarchical protocols . . . 38

2.4.4 Geographic routing . . . 42
2.5 Network modelling and simulation . . . 43
2.5.1 Simulators for WSNs . . . 44
2.6 Summary . . . 45

3 Medium access in large scale clusters 47
3.1 Introduction . . . 47
3.1.1 Objectives . . . 48
3.1.2 Related work . . . 49
3.2 Scalability in wireless sensor networks . . . 51
3.2.1 Scalability of other systems and networks . . . 51
3.3 Scalability of Clustering Algorithms . . . 52
3.3.1 Cluster formation . . . 53
3.3.2 Large scale clusters . . . 54
3.3.3 Hardware selection and cluster set-up . . . 55
3.3.4 Intra-cluster communication . . . 56
3.4 Collisions and hidden nodes . . . 58
3.5 Medium access strategies . . . 62
3.6 Simulations and results . . . 66
3.7 Discussion . . . 71
3.8 Summary . . . 72

4 Cluster routing 73
4.1 Introduction . . . 73
4.1.1 Objectives . . . 74
4.1.2 Assumptions . . . 74
4.1.3 Related work . . . 75
4.2 Energy usage in WSNs . . . 76
4.2.1 Single-hop vs. Multi-hop . . . 76
4.2.2 Energy distribution . . . 81
4.3 Cluster communication . . . 82
4.3.1 Cluster formation . . . 82
4.3.2 Half Distance Relay . . . 84
4.3.3 Single Relay Decision . . . 85
4.3.4 Multiple Relay Decision . . . 85
4.4 Simulation . . . 87
4.5 Simulation results . . . 89
4.5.1 Algorithm evolution . . . 89
4.5.2 Performance evaluation . . . 90
4.5.3 Network lifetime . . . 92
4.5.4 Mean communication distance . . . 94
4.5.5 Sum of queued messages . . . 95
4.6 Discussion . . . 97
4.7 Summary . . . 99

5 WSN simulation and environment-aware communication 101
5.1 Sensor network simulation . . . 101

5.1.1 Challenges 102
5.1.2 Assumptions and definitions 102
5.2 Modelling wireless communication 103
5.3 Simulator architecture 106
5.3.1 Nodes and CH tables and status 107
5.3.2 Energy 109
5.3.3 Simulation clock and runtime 110
5.3.4 Packet and channel handling 111
5.4 Network algorithms 111
5.4.1 Routing 111
5.4.2 Medium Access Control 112
5.4.2.1 Physical layer 112
5.5 Opportunistic routing in blind nodes 113
5.6 Environment-aware communication 115
5.6.1 Related work 116
5.6.2 The environment engine 116
5.6.3 Adapting network behaviour 118
5.6.4 Routing selection rules 118
5.6.5 Adaptive routing decision 119
5.7 Summary 120

6 Simulation results 121
6.1 Simulation parameters, methodology and assumptions 121
6.1.1 Output metrics 124
6.2 Single-hop results 126
6.2.1 Packet delivery and range 127
6.2.2 Mean distance between origin and CH 129
6.2.3 Energy 130
6.2.4 Discussion 131
6.3 Multi-hop results 132
6.3.1 Greedy routing 132
6.3.2 Two-hop results 135
6.3.3 Discussion 140
6.4 Opportunistic routing results 141
6.4.1 Greedy results 141
6.4.2 Two-hop results 142
6.4.3 Discussion 143
6.5 Environment engine results 144
6.5.1 Routing decision 145
6.6 Discussion 146
6.7 General discussion 146
6.8 Summary 150

7 Conclusions 151
7.1 Summary 151
7.1.1 Medium Access Control 151
7.1.2 Two-hop routing 152

7.1.3 Environment-aware simulation and results 153
7.1.4 Environment-aware engine 153
7.2 Contributions 154
7.3 Future work 155
7.3.1 Two-hop routing and cross-layer development 155
7.3.2 General-purpose adaptive network routing 156
7.3.3 WSN deployment at sea 156

Bibliography **157**

Simulation results **171**

Selected publications **185**

List of Figures

1.1 General diagram of sensor network development. 3
1.2 Generic vision of a WSN deployment on an oil slick. 6
1.3 Beaufort scale, relating wind speed and wave height. 6
1.4 Ideal waves and related terms. 7
1.5 Challenges for localised maritime monitoring. 11
1.6 Structure of the thesis, relating the main themes with the chapters where they are mentioned. 14

2.1 Components in a WSN node. 18
2.2 Comparison of different protocol stacks (OSI, TCP/IP, WSN generic model). 21
2.3 Number of nodes alive using simple single-hop routing and the ideal protocol. 23
2.4 Energy break for Telos mote. 24
2.5 Nodes arranged in sequence, where each one communicates only with its close neighbours. 26
2.6 802.15.4 star and peer-to-peer topology. 27
2.7 ZigBee stack over 802.15.4 protocol. 28
2.8 Hidden terminal problem. 30
2.9 Exposed terminal problem. 30
2.10 Basic RTS/CTS mechanism, where a Short Inter-Frame Space (SIFS) represents the time it takes for nodes to receive, process and transmit frames. 31
2.11 Two problems in RTS/CTS handshake. 32
2.12 Routing protocols division. 34
2.13 Simplified schematic for directed diffusion. 36
2.14 The SPIN protocol. 37
2.15 Example of spanning tree where one coordinator (black node) controls the connectivity and links between members (grey). 39
2.16 Example of a three-tier cluster, where the CH of each layer communicates the gathered data across to other CHs and ultimately to the sink node. . 40
2.17 Cluster taxonomy and attributes. 43

3.1 FLOC state transition. 50
3.2 Ideal cluster division and CH placement. 54
3.3 Examples of cluster deployment in a 5000 × 5000 metre area. 57
3.4 Deployment example with 2500 sensing nodes in a 5000 × 5000 metre area, $R_{Tx} = 1000m$, $\epsilon = 300m$. 58

3.5 Probability of any two nodes in the network selecting the same transmission time. . . . 59
3.6 Probability of any other node selecting the same time slot as n_i. 60
3.7 Probability of collision between two given nodes without collision avoidance. 61
3.8 Probability of collision between two given nodes with collision avoidane. . 62
3.9 Single retransmission mechanism based on the division of T into two periods. 64
3.10 Multiple retransmission mechanism with skewed curves. 65
3.11 Curves used for the probability distribution across the period. 66
3.12 Packet delivery (blue) and collision (red) for single transmission access methods. . . . 68
3.13 Energy usage estimation for one period using single transmission access methods. . . . 68
3.14 Energy efficiency for one period using single transmission access methods. 69
3.15 Packet delivery (blue) and collision (red) for single retransmission mechanism through period division. . . . 69
3.16 Energy efficiency for retransmission mechanism through period division. . 70
3.17 Packet delivery (blue) and collision (red) for multiple retry with curve fitting model. . . . 70
3.18 Energy efficiency for multiple retry with curve fitting. 71

4.1 Distance between three nodes. 77
4.2 Total power required by nodes to send one message each to CH using single-hop and multi-hop with different transceiver gains, where 1 corresponds to the power required for a single transmission. 79
4.3 Energy saving ratio between multi-hop and single-hop for different Y location and g values when $/eta = 2$. . . . 80
4.4 Energy saving ratio between multi-hop and single-hop for different Y location and g values when $/eta = 3$. . . . 80
4.5 Energy saving ratio between multi-hop and single-hop for different Y location and g values when $/eta = 4$. . . . 81
4.6 Node Y's ideal location with different values for g, when $e = 10$. 82
4.7 Displacement of nodes around CH. 83
4.8 Example of potential routing paths. 84
4.9 HDR ideal position and selection region. 85
4.10 Example of weights in different paths. 87
4.11 Routing decision flowchart. 89
4.12 Example of a network evolution using a single-hop algorithm. 90
4.13 Example of a network evolution using a greedy algorithm. 91
4.14 Example of a network evolution using the HDR algorithm. 92
4.15 Example of a network evolution using the SRD algorithm. 93
4.16 Example of a network evolution using the MRD algorithm. 94
4.17 Number of nodes alive in the cluster. 95
4.18 Mean communication distance in a cluster. 96
4.19 Number of messages accumulated across the network. 97

5.1 Communication diagram for correct transmission decision. 104
5.2 Geometric representation of BER according to changes in SINR. 106
5.3 Simulation modules and their interaction. 107

5.4 Transmission sequence diagram. 108
5.5 Node communication stack. 109
5.6 Message relaying process. 109
5.7 Message creation and routing decision sequence in nodes. 110
5.8 Diagrams where only visible nodes transmit (left) and with added communication from opportunistic blind nodes right. 113
5.9 Proactive tree building in blind nodes. 114
5.10 Reactive tree building in blind nodes. 114
5.11 Simplified control diagram for adaptive WSN behaviour. 116
5.12 Environment engine framework and its positioning in a WSN node's architecture. 117
5.13 Adaptive model for environment manager. 118

6.1 Packet delivery for SH routing with PL between 2 and 5, and H between 0.2 m and 2 m. 128
6.2 Collision rate for SH routing. 128
6.3 Simulated packet delivery as a fraction of theoretically estimated rate. . . 129
6.4 Mean distance between origin and CH, in metres. 130
6.5 Energy usage for SH routing. 131
6.6 GR packet delivery as a fraction of SH. 133
6.7 Network latency with GR routing. 134
6.8 Collision rate as a fraction of correctly received messages by the CH, for GR routing. 134
6.9 Mean distance between origin and CH for each received message as a fraction of SH. 135
6.10 SRD packet delivery as a fraction of SH. 136
6.11 MRD packet delivery as a fraction of SH. 136
6.12 Mean distance between origin and CH with SRD routing as a fraction of SH. 137
6.13 Mean distance between origin and CH with MRD routing as a fraction of SH. 137
6.14 Collision rate for SRD routing. 138
6.15 Collision rate for MRD routing. 138
6.16 Network latency with SRD routing. 139
6.17 Network latency with MRD routing. 139
6.18 Packet delivery for GR opportunistic routing as a fraction of SH. 142
6.19 Mean distance between origin and CH for each received message as a fraction of SH. 142
6.20 Packet delivery for MRD with opportunistic routing as a fraction of SH. . 143
6.21 Mean distance between origin and CH with MRD routing as a fraction of SH. 144
6.22 Geometric representation of routing decision. 145

List of Tables

2.1 Voltage and current consumption by standard WSN transceivers. 23
2.2 Energy usage for Telos mote using 1% duty cycle, with 3 V supply voltage. 24

3.1 Simulation parameters. 67

4.1 Simulation parameters. 88
4.2 Messages used by cluster head and nodes during the simulation. 88

5.1 Packet types used in the simulation. 108
5.2 Algorithm's scores for packet delivery and range. 119

6.1 General simulation parameters. 122
6.2 Environment-specific parameters. 123

1 Packet delivery with SH routing. 172
2 Mean distance between origin and CH with SH routing. 172
3 Collision rates with SH routing. 173
4 Energy used by nodes with SH routing. 173
5 Delivery rates with GR routing. 174
6 Mean latency with GR routing. 174
7 Collision rate with GR routing. 175
8 Mean distance between origin and CH with GR routing. 175
9 Delivery rates with SRD routing. 176
10 Mean latency with SRD routing. 176
11 Collision rate with SRD routing. 177
12 Mean distance between origin and CH with SRD routing. 177
13 Delivery rates with MRD routing. 178
14 Mean latency with MRD routing. 178
15 Collision rate with MRD routing. 179
16 Mean distance between origin and CH with MRD routing. 179
17 Delivery rates with GR opportunistic routing. 180
18 Mean latency with GR opportunistic routing. 180
19 Collision rate with GR opportunistic routing. 181
20 Mean distance between origin and CH with GR opportunistic routing. . . 181
21 Delivery rates with SRD opportunistic routing. 182
22 Mean distance between origin and CH with SRD opportunistic routing. . 182
23 Delivery rates with MRD opportunistic routing. 183
24 Mean distance between origin and CH with MRD opportunistic routing. . 183

Declaration of authorship

I, Pedro N. E. S. Barbosa, declare that this thesis entitled 'Scalable Wireless Sensor Networks for Dynamic Communication Environments: Simulation and Modelling' and the work presented in it are my own and has been generated by me as the result of my own original research.

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. Parts of this work have been published as listed in section 1.5 of this thesis.

Signed: ....

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Nomenclature

Abbreviations

ACK	Acknowledgement
ADC	Analog-to-Digital Converter
BER	Bit Error Rate
BS	Base Station
CA	Collision Avoidance
CD	Collision Detection
CH	Cluster Head
CSMA	Carrier Sense Multiple Access
CTS	Clear-To-Send
GPS	Global Positioning System
GPSR	Greedy Perimeter Stateless Routing
GR	Greedy
HDR	Half Distance Relay
IP	Internet Protocol
kbps	kilo bits per second
MAC	Medium Access Control layer
MCU	Microcontroller Unit
MRD	Multiple Relay Decision
OSI	Open Systems Interconnection
PHY	Physical network layer
PL	Path Loss exponent
QoS	Quality of Service
RF	Radiofrequency
RTC	Real-Time Clock
RTS	Request-To-Send
RV	Random Variable
Rx	Reception
SH	Single-Hop
SINR	Signal-to-Interference-to-Noise Ratio

SNR	Signal-to-Noise Ratio
SRD	Single Relay Decision
TCP	Transmission Control Protocol
Tx	Tansmission
WSN	Wireless Sensor Network

List of symbols

A_{CH}	Cluster area
B	Communication bandwidth
c	Speed of light $[3 \times 10^8 m/s]$
C_i	Inverse weight of a path i
d	Transmission distance [m]
E	Energy [J]
η	Path loss exponent
ϵ	Accuracy error
f	frequency [Hz]
γ	Acceleration due to gravity
g	Gain factor of transmission over reception
G	Gain [dB]
h	Antenna height above water level
k	Boltzamann constant $[1.381 \times 10^{-23} J/K]$
L_P	Path loss [dB]
H	Wave height
N	Nodes
N_0	Noise power
n_i	Node i
ρ	Probability of a node transmitting at a given time slot
$p(n)$	Probability of a node n transmit in a time slot
P_i	Probability of using a path i towards the CH
$\rho(N, t_j)$	Probability of at least one node transmitting at time t_j
$\rho(n_i)$	Probability of node n_i transmitting in a time slot
$q(n)$	Probability of any other node transmitting at the same time as n
P	Power [W]
R	Two-hop relay region
t	Single transmission time
T	Transmission period
τ	Temperature
W	Communication weight
X_σ	Gaussian zero-mean random variable

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To my mother, Margarida.

Chapter 1

Introduction

Continuous monitoring of environmental aspects and tracking of phenomena has been made possible through developments in electronics and computing. Wireless Sensor Networks (WSNs) is where a number of small and inexpensive devices operate together to allow distributed sensing and tracking. Each device is fitted with sensing, processing, communication and power supply hardware [1]. Combined, these devices form a collaborative network structure that senses the environment, processes that data locally and shares the resulting information with surrounding devices and other networks.

Wireless Sensor Networks often envision circumstances where devices are rapidly deployed in remote or nearly inaccessible locations [2]. Typical application examples include: battlefield monitoring [1], using devices with a few cubic millimetres in size are thrown off aeroplanes to collect information about the environment or track enemy troops; industrial environment sensing and actuation [3], with devices strategically positioned in factories to identify when unexpected events can become potentially dangerous; environmental monitoring [4, 5], with devices deployed in natural habitats to study geophysical events or assess the impacts of changing environment; and healthcare, where the physiological activities of patients are continuously monitored with sensors, either preventively or during recovery [6]. In most of the examples, application constraints or logistic drawbacks do not allow the installation of cabled networks [7, 8]. In such cases, WSNs are the only option to successfully monitor the areas of interest.

1.1 Wireless sensor networks

The WSN concept is accomplished due to the development of three different areas of electronics: wireless communication, sensing devices, and low power hardware. WSNs are composed of small devices called *nodes* that are distributed over a region and expected to operate autonomously. The original vision aimed at creating tiny, inexpensive nodes to be deployed in a very large scale, creating networks with thousands or even millions of devices. However, technological limitations resulted in greater node sizes and smaller deployments. Furthermore, new applications and their demand for faster prototypes led to more powerful nodes running complete operating systems. As such, technological and application-related aspects resulted in the design of two different solutions [9]: simple and inexpensive on one hand, and more powerful and flexible on the other.

There are several aspects inherent to the node design:

Node size. If a node needs to be carried by someone (a patient, for example) its size is of significant impact to the usability. On the other hand, static nodes in environmental monitoring have fewer size limitations. Instead, the application demands robustness to withstand any interference or physical damage.

Energy. To allow greater independence and flexibility, there are no wires connecting nodes to external power supplies. Instead, each node relies on its own power supply which must last long enough for a successful data collection, commonly translated into months or years.

Processing demands. Nodes have a limited number of tasks, according to the network purpose. As such, 8-bit and 16-bit microcontrollers with limited processing, memory and low power consumption are commonly found in nodes. On the other hand, the demands of particular and more complex tasks can require more than a microcontroller. For such cases, there are nodes based on 32-bit microprocessors, with similar features to those of embedded PCs.

Communication. When a node transmits its data across, it assumes that the channel is reliable enough to guarantee the correct reception. Using a radio that is suited to the deployment conditions is the first step to ensure a correct operation. It implies using adequate frequency, transmission power and coding scheme, among others.

Packaging and robustness. Nodes designed for domestic deployment do not need to be as robust as those designed for industrial applications. Same considerations apply to nodes designed to be used either indoors or outdoors. Sensing, packaging and communication will face different challenges and demands in different environments.

Decision autonomy. Nodes are expected to work without external supervision and maintenance during extended periods of time. To do so, they must have a decision scheme that allows flexibility to deal with unexpected situations and proceed with normal operation.

All these challenges are closely related. Nodes are embedded platforms which demand a trade-off between minimum and optimal requirements to better suit a particular deployment. Therefore, the application scenario is one of the integral and fundamental aspects of the WSN development. A correct description details the foundations for a successful network. It can be summarised in terms of deployment method, coverage area, sensing and actuation, potential obstacles, mobility, and possible local resources that the nodes can use for their benefit. Without this description, it is not possible to say which parameters are the most important and what is the degree of influence between them. As such, there is no general solution for WSNs. The combination of architectural and application factors presents a unique set of challenges that must be overcome for a successful deployment and operation. These factors will be used to select hardware, network protocols and how to configure the network in detail. Evaluation metrics are also derived from the requirements and used to evaluate how the WSN performs under the deployment conditions. This general approach to the WSN design is shown in figure 1.1.

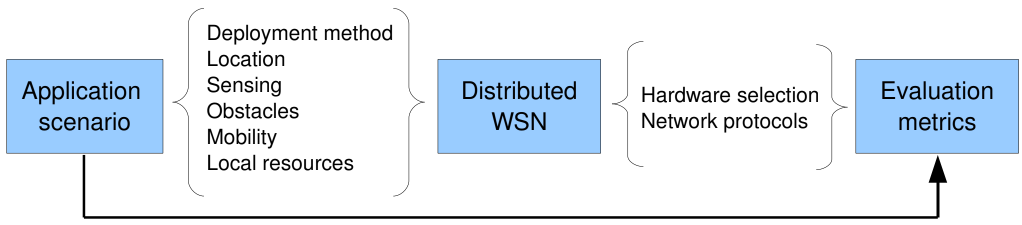

FIGURE 1.1: General diagram of sensor network development.

A WSN purpose is therefore to use distributed nodes working cooperatively to achieve a degree of success that would not be possible if they worked individually. Independently of particular decisions, sensor networks are expected to correspond to general requirements:

Network lifetime. Although it is not always possible to estimate accurately the expected lifetime during operation, a worst-case scenario estimation assures a minimum operational time. Furthermore, optimisation through cooperation explores the best solution to this problem and aims at maximising sensor and network lifetime.

Coverage area. The size of the area to be monitored affects sensing accuracy and communication between nodes. This will impact on power consumption and network connectivity graphs.

Network density. Empirically, the more nodes there are in a particular region, the greater the competition is for the same wireless spectrum, thus the higher the collision rate. Local topology management can assist with a correct decision regarding how to structure the network and improve communication between nodes.

Adaptability. Nodes must form a network, independently of their number, physical characteristics or deployment location. Each node is expected to be in range of at least another node (ideally more than two), and must guarantee that data will be sent to any destination with the lowest impact on overall performance.

Cooperative work. To take full advantage of the network abilities and overcome individual limitations, sensor networks work cooperatively to find the best fit and minimise individual errors. Cooperation improves sensing accuracy, network robustness and overall lifetime.

Communication robustness. The communication link between two nodes can be interrupted at any time by external factors. Nodes must therefore include mechanisms that guarantee minimal data loss by identifying when the connectivity is low or inexistent and finding alternative routes whenever possible.

Redundancy. By deploying more nodes than required, data accuracy and reliability are improved. On the other hand, network redundancy results in increased bandwidth usage, thus higher contention and collision rates.

Latency. Data delivery rate will depend on network size and channel availability. Latency (or end-to-end delivery time) grows with the number of nodes and their impact on bandwidth. The greater this delay is, the higher the number of packets waiting to be transmitted is and the less usable the network becomes.

Mobility. In mobile networks, nodes will change neighbours at some point in time. Establishing new routes and keeping its vicinity list constantly updated presents a challenge in terms of bandwidth usage and routing table size.

Network expansion. New nodes can be added into a WSN at any time, integrating and cooperating with existing ones. Data forwarding, aggregation and load sharing are three possible alternatives for cooperation between nodes.

Sensing coverage. Node sensing is done in a single point and dependent on location. More nodes are needed to expand coverage or increase precision. For example, Siuli Roy and Bandyopadhyay [10] used 300 nodes across 26.7 ha for precision agriculture, while Mainwaring et al. [11] used 32 nodes to monitor a 95.9 ha region for habitat monitoring.

Security. An operating network must accept new nodes, as long as they prove trustworthy. Intruders, on the other hand, must be quickly identified, denied access to content and stopped from both broadcasting irregular content or taking over the available bandwidth. Threats were identified by Avancha et al. [12], and they are mainly due to hardware simplicity. Nevertheless, current communication standards already include encryption and other security features.

Considering all the aspects inherent to node and cooperative network design, a clearly described case scenario is essential to a successful WSN deployment. The scenario description must encompass the network purpose and expected challenges. Furthermore, it must also look into other monitoring alternatives to assess the feasibility and performance metrics.

1.2 Case scenario

There is a high degree of uncertainty with maritime events: they are often unexpected and can occur anywhere. Using the example of oil spills at sea, they can occur anywhere where oil tankers navigate or where underwater pipelines and platform rigs are installed. Given the amount of oil spilled, the potential extension of the affected area can extend to several hundreds of square kilometres. In addition, slicks can have irregular shapes and keep adrift for weeks.

Currently, maritime monitoring is performed mainly by satellite image processing and airborne sensors using infrared/ultraviolet sensors, Light Detection And Ranging (LIDAR) [13] and synthetic aperture radars (SAR) [14, 15]. Local monitoring can be performed recurring to Argos transmitters [16] or the Genesis alert system [17]. Each method presents different advantages and limitations: satellites cannot keep continuous monitoring over one region, airborne radars depend on the aeroplane time of flight, and the local monitoring devices are not designed for wide area deployment with a high number of devices.

1.2.1 WSNs for localised maritime monitoring

Having a wireless sensor network covering an area of the sea where pollutants such as oil slicks are drifting can be seen as a complement to satellite and airborne monitoring. The WSN can be quickly deployed over a region and nodes, once drifting, start communicating between each other immediately. They organise themselves into a network that provides means of sending the sensed data (i.e. thickness or chemical composition) across to *sink nodes*, responsible for aggregating and transmitting that data over to remote locations for further analysis. A simplistic vision of a WSN deployment is shown in figure 1.2, where nodes (yellow dots) are drifting at sea in a region where oil was spilled.

WSNs allow continuous monitoring of a region under different weather conditions. As such, the use of sensor networks for localised monitoring on the contaminated area provides a distributed, flexible and robust solution that can be deployed anywhere and left to operate autonomously. Ideally, the network would monitor the complete slick. Yet, as the slick can extend up to several hundreds of kilometres, localised monitoring

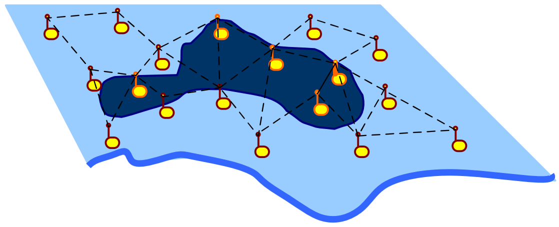

FIGURE 1.2: Generic vision of a WSN deployment on an oil slick.

Wind speed (km/h)	0-5	6-11	12-19	20-28	29-38	39-49	50-61	62-74	75-88	89-102	103-117	≥118
Wave height (m)	≤0.1	0.2	0.6	1	2	3	4	5.5	7	9	11.5	≥14
Beaufort number	1	2	3	4	5	6	7	8	9	10	11	12

<——— **Weather conditions** ———>

FIGURE 1.3: Beaufort scale, relating wind speed and wave height.

of areas up to a few square kilometres is a more realistic approach. By analysing data from other surveillance devices, it is possible to discover locations where the deployment of WSNs is more relevant. The accuracy of the sensor network should be comparable to that of Synthetic Aperture Radars (SARs), which is in some cases less than 75 metres (resulting in more than 175 nodes per square kilometre) [14]. Also, the network is expected to drift with the slick and send the data in near real-time back to a base station, independently of how the network moves or expands in coverage area.

The WSN deployment allows the monitoring of different parameters locally. Absolute location, oil thickness, chemical substances present, slick dispersion and depth are some of the possible aspects to be sensed. The monitoring is continuous, even during cleaning, thus it is possible to have feedback from the procedure, maximising its effectiveness and precision.

Oil slick monitoring presents a unique combination of challenges. The location, trajectory, speed, size and shape of the slick are unpredictable. Furthermore, the weather conditions can quickly change from calm to harsh and vice versa. These condition demand resilience and adaptability from communication and sensing modules. On the two extremes, and according to the Beaufort scale [18], the wind can go from calm, with a speed below 1 km per hour, to hurricanes, where it reaches speeds over 100 km per hour. Wind speed is directly related to wave height, as can be seen in figure 1.3.

1.2.2 Ocean surface waves

The greatest challenge to sensor deployment at sea comes from waves. They will influence the communication in two ways. First, as waves appear in the path between origin and destination, they block the communication. The rougher the sea, the longer the blocking time. Second, as antennas are traditionally directed in the horizontal plane, excessive node swing will result in lower transmitting power towards the destination.

Surface waves are generated mainly by friction, with the wind dragging the water surface [19]. The basic approach considers waves as being ideal sinusoidal curves, as can be seen in figure 1.4. Nevertheless, there is no direct relation between wave height H (or the distance between trough and crest) and wave length Λ (or the distance between two crests).

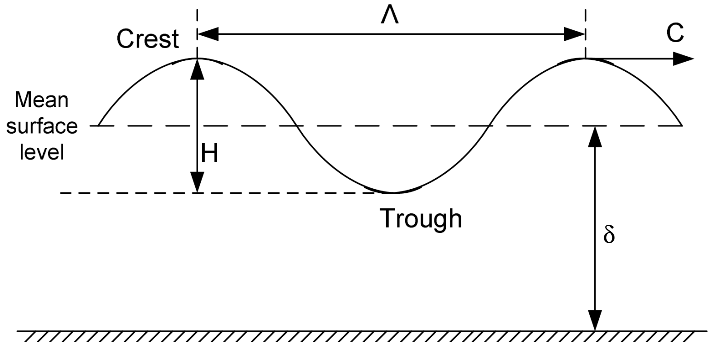

FIGURE 1.4: Ideal waves and related terms.

Ocean waves are divided into several groups, as described by Pond and Pickard [20]. Ripples, wind waves and swells are due to the wind effect on water. Ripples and wind waves are generated locally and differ from each other in wave length and frequency, wind waves being bigger and less frequent than ripples. Swells are generated elsewhere and their direction is more regular.

There are two distinct regions for waves: shallow water and deep water. In deep water, where the depth δ is at least twice the wave length, the relationship between wave speed C and wave length Λ is $C = \Lambda/\Gamma$, where Γ is the wave period. In shallow water the wave speed is proportional to the wave depth, $C = \sqrt{\gamma\delta}$, where γ is the acceleration due to gravity. The wave height H is independent of wave speed, wave length or period, yet it is limited by breaking (the point where the base can no longer support the top of the wave, making it collapse).

Understanding waves is therefore of major importance, as their shape, speed and frequency will have direct effect on communication, to the extent of making the network inoperative. Nevertheless, it is possible to use this information to understand and maximise the operating conditions.

1.2.3 Deployment of sensor networks at sea

Sensor Networks were previously deployed at sea to support different tasks. The SECOAS project [21, 22] used fixed sensors distributed through a wind farm to study the sedimentation and wave process and its effect on wind turbines. The network consisted of 6 fixed sensor nodes equipped with 173.25 MHz radios. Despite variable weather conditions, from very calm to heavy rain, strong winds and 3 metres high waves, the radios successfully sent their messages to a base station located 3 km away. Another project using WSNs at sea was developed by Nittel et al. [23]. The objective of the project was to deploy sensor nodes on the ocean surface to track and monitor ocean currents. The nodes would allow fine grained and near real-time scale. As a preliminary study, it did not give any significant results from the deployment trials. The global drifter program [24] aims at deploying drifters in large-scale, with the goal of mapping ocean's surface circulation. The drifters provide near real-time information about speed, temperature and sea level pressure. A total of 658 drifters were deployed around the world between 2003 and 2004, sampling data every 90s and sending it through satellite. The sensor density is lower to what is envisioned for oil slick monitoring, as the main goal is to maintain 5 degrees coverage.

Rajasegarar et al. [25] installed a sensor network on the great barrier reef, in Australia. The authors aimed at developing an adaptive solution that could provide reliable communication independently of weather changes, based on wave dynamics and node trajectory which, despite being fixed to the sea floor, were capable of drifting within a delimited region, causing loss of communication. The OceanSense project [26] consisted of 18 nodes deployed off the coast of China for 6 months, on an area of approximately 100m$\times$300m, monitoring temperature, light and RSSI. Cella et al. [27] deployed a 10 node network to monitor the coastline in Queensland, Australia. Although the network used wireless radios, the authors argued that underwater communication could solve some issues that occurred during its deployment.

1.3 Research contribution

Wireless sensor networks is a technology that demands a detailed description of the deployment scenario. The tight restrictions inherent to the concept mean that, in order to achieve the best compromise between requirements, specific decisions are needed for the set of characteristics to be found. In the particular case of a maritime deployment, there is a high variability of weather conditions, affecting mainly communication between nodes. In addition, there is a degree of uncertainty about the network size, as it can vary significantly between deployments to cover the affected region. Therefore, the contributions of this thesis depart from the application scenario to design communication strategies, resulting in an holistic decision process that leads to the development of novel algorithms and solutions.

1.3.1 Justification and motivation

Directives 2005/35/EC from the European Parliament and Council [28] and Council Framework decision 2005/667/JHA [29] introduced penalties to infringements of ship-sourced pollution across the European Union. The sinking of Erika and Prestige oil tankers, as well as the high number of deliberate spills detected (due to tank cleaning and waste oil disposal, for example) led to the need for better monitoring of sea water. Although the largest spills are those causing the highest mediatic impact, smaller ones are more frequent in number. As an example, in 2001 there were 390 oil slicks detected in the Baltic Sea and 596 in the North Sea [30]. Entities such as the European Maritime Safety Agency [31] contribute to the monitoring of the seas, mainly through satellite sensing. Localised, distributed sensing mechanisms can be used to expand and complement these surveillance methods once the spill has been detected, providing further information about its content, size and trajectory.

Simulation environments are frequently used to test the feasibility of the theoretical solutions found [32]. Alternatives to simulation use numerical modeling or real deployments, with sensors thrown at sea, providing real feedback about operating conditions and performance of algorithms. The deployments can be done in smaller scale or lakes, for simplicity and ease of access. Nevertheless, this option would impose restrictions to the full development, mainly due to the time and cost that it represents to achieve the same set of results. In addition, any modification and optimisation of algorithms would rely on collection, programming and re-deployment of nodes.

There are two key issues in application-specific WSN development: sensing and communication. They have direct or indirect impact on the design decisions and ultimately determine the concept's feasibility. Considering the dynamics inherent to waves and network topology, communication is believed to be of primary interest to the concept. Furthermore, the decisions and findings regarding data exchange will also reflect on node displacement, network size and sensor selection. A key issue in communication and data exchange comes from the network algorithms and protocols.

Several alternatives can be used for network algorithms. They serve either for general-purpose applications or target specific and well-defined cases. To the best of the author's knowledge, existing solutions do not envision the challenges found in large-scale, offshore maritime monitoring scenarios in a single work and comprising different layers of the network stack as described in this thesis. Weather conditions can change dramatically, even in the period of one day, which will impact on the communication between nodes. WSN development often considers a limited operation scope and uses it for algorithm development. In a maritime monitoring scenario it is obligatory to consider a broad set of conditions, otherwise the performance can be compromised to the extent of making the network unusable. On the other hand, to achieve a resolution comparable to that of satellite imaging, this research must also identify the best method to connect a network that can extend up to several thousands of nodes.

The combination of both weather and displacement challenges creates a unique set of conditions, hence requiring novel solutions. In addition, the resource limitations of nodes demand for approaches that can cope with application constraints while keeping an acceptable performance.

1.3.2 Aims

The main aim of this research is to create a sensor network that operates under variable environmental conditions at sea. It is expected that weather and node displacement vary considerably during network operation, thus the WSN must adapt its behaviour to achieve the best compromise at any time. Maritime monitoring is used as the application scenario. The displacement variations correspond to network size, node location, covered area and transmission range, while the weather changes compromise path loss due to moisture or rain and attenuation from waves.

This thesis comprises a bottom-up design of a WSN. The different parts are analysed first separately, then combined. From an individual analysis of parts, it is possible to find the best compromise, which will then be combined to form a complete architecture. Starting from the application scenario described above, networking algorithms are chosen and compared. They are divided into two different network stack layers, and their initial development is done separately. After deciding which options fit the application best, a complete simulator with realistic weather models is built and the algorithms are matched and implemented together. Finally, with the complete set of results from the simulator, an adaptive model is designed to adjust the network according to the current environmental conditions found.

This thesis is divided into the following themes:

Medium Access Control for large-scale networks. The development of the lower layers of the network stack must concur with the remaining stack. Therefore, MAC algorithms are as important as their routing counterparts. This involves understanding the factors affecting the layer's operation, such as collisions and hidden nodes, and minimising their impact under the existing constraints.

Routing algorithms. Each application has its particularities that demand purposely designed routing algorithms. The design takes into account the network characteristics, such as size and node displacement, and provides the best alternative for

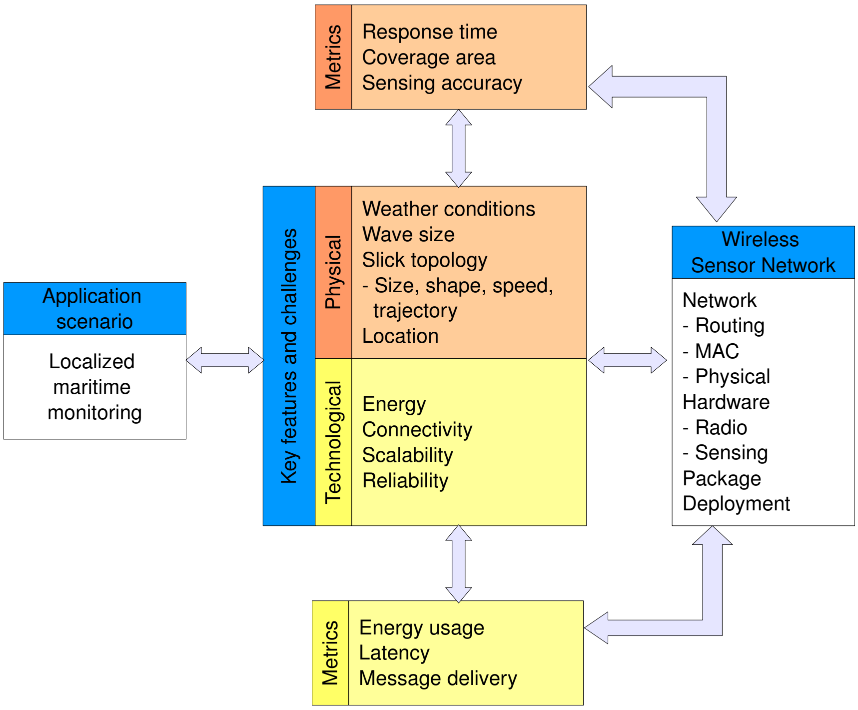

FIGURE 1.5: Challenges for localised maritime monitoring.

an optimal operation. One of the crucial aspects to routing is to understand the advantages and disadvantages between individual and collaborative decisions,

Adaptive, environment-aware communications. When conditions change, nodes may need to adjust their behaviour accordingly. Knowing how the change occurs and how it affects the network parameters is key to achieving the best performance.

Adaptive network behaviour. Changes in weather and network topology lead to different outputs from the chosen algorithms. If the network adapts its behaviour according to a figure of merit, it can achieve optimal scores under any given situation. Considering a combined output score for each algorithm, a figure of merit is derived to allow a direct comparison between them.

1.3.3 Scope and challenges

Adapting the network to work optimally under a variable environment requires an understanding and adjustment to weather in the deployment area, the hardware in use and the network characteristics. These features and challenges can be divided into two categories, physical and technological, each of them describing the range of specific parameters. These parameters are further related to evaluation metrics, as shown in figure 1.5.

There are two main challenges from WSN deployment at sea: oil slick dispersion and waves. Murray [33] showed that the oil slick dispersion follows known regimes, therefore its influence in the deployment can be estimated. Surface waves, on the other hand, are random. They can interfere with the deployment in two ways: block the line of sight between two sensors, causing shadowing; and tilt the sensor node, making nodes transmit towards the water or the sky. Smaller waves can be avoided by placing antennas higher. However, as higher antennas increase tilting, the maximum height is limited. Furthermore, and deriving from hardware, algorithms and environmental constraints, connectivity graphs, message delivery, latency, collision rate, and energy consumption are some of the parameters affected by the network set-up.

The Beaufort scale leads to an empirical estimation of the operation range of a WSN at sea. On the left side of the graph of figure 1.3, it is empirically expected that the WSN works with minimal weather interference, thus the challenge is to optimise secondary parameters with the lowest impact on the main ones. On the other extreme, as weather interferes severely with the communication channel, the main aim is to guarantee message delivery at any cost. Between extremes, a balanced solution is possible.

On the sensor node side, due to the intricate interactions between hardware and firmware, energy saving is a basic premise to keep the energy consumption low and allow the network to run for months or even years. To do so, sensing, processing and communication frequency are reduced, and low power hardware is chosen. This results in limitations that affect the node's performance.

In addition to the single sensor, there are the network-wide challenges that influence the individual node's behaviour. There is a need to balance between aggressive energy savings and collaborative resource usage. Where one node's greediness can result in a less-than-optimal network behaviour, a trade-off between self and global interest can improve overall performance.

Complementing single-node and network-wide perspectives, a deep understanding of the interaction between the network and the environment is the final input to the design and development of a WSN. It defines the constraints, challenges and limitations that will influence both hardware and firmware decisions. As such, only a holistic approach that combines all the related areas lead to the correct decisions for individual component selection. Ultimately, these decisions will impact on the data collection and information sharing between the network and the end user.

1.3.4 Contributions

The research presented in this thesis is based on networking aspects of WSNs. Starting from the application scenario, this thesis proceeds with the hardware selection and the design of network algorithms. This results in the following contributions:

Variable size and topology networks: Being a completely distributed system with limited resources, WSNs require novel approaches and solutions to cope with the network dynamics. Considering the application scenario, the selection of network algorithms must take into consideration the effects of variable network topology and size to minimise their impact on the communication process.

Medium access mechanisms: Efficient medium access control is fundamental to save energy, improve packet delivery and bandwidth usage. The problems affecting this layer are normally hidden from the above ones. By using different access schemes it is possible to compare how they affect the network performance.

Energy distribution: There are trade-offs between simple and complex network algorithms, affecting energy consumption in nodes directly. Furthermore, limitations in hardware resources and the deployment constraints demand simplicity and efficiency.

Environment-aware communication. The focal point of this research is the understanding of how environment influences network behaviour. By combining data to generate performance metrics and using them to modify routing algorithms accordingly, it is expected to improve communication between devices when environmental conditions change.

1.4 Thesis structure

This work presents the results of a study of a WSN designed for weather-aware maritime monitoring. Figure 1.6 outlines the thesis structure and the relation between the addressed themes.

The second chapter will focus on a WSN survey, introducing related concept in more detail. Due to the scope of this research, a greater focus is given to concepts associated with low-power, distributed wireless network hardware, algorithms and protocols.

The third chapter presents a study concerning Medium Access Control performance. It compares different types of access methods, with and without contention, and provides the results in terms of packet delivery, collision probability and energy usage.

The fourth chapter gives an insight into energy usage and consequent node lifetime in a cluster. Routing algorithms based on two-hop relay for intra-cluster communication are described in this chapter. They rely on a weight function to decide the best routing alternative inside a cluster. Results and comparison with other routing protocols are also shown.

Chapter 5 details the realistic channel, interference and weather models. These were implemented in the custom-built simulator used to test the algorithms of chapters 3

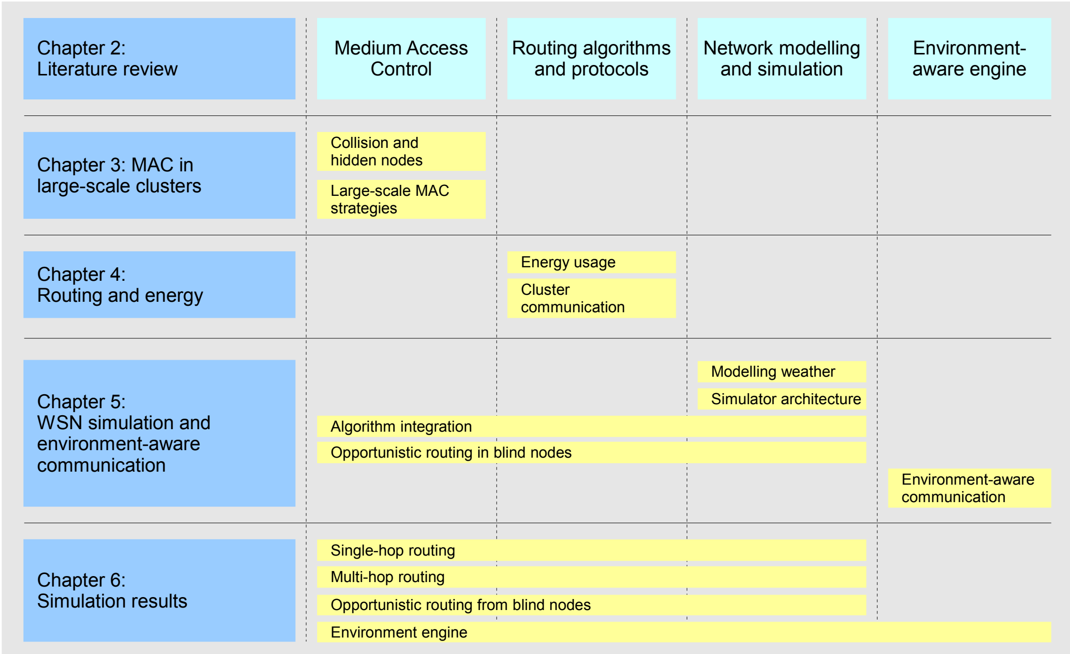

Figure 1.6: Structure of the thesis, relating the main themes with the chapters where they are mentioned.

and 4. Chapter 5 also describes the environment-aware engine and the decision rules to assess the network performance.

Chapter 6 presents the results obtained from the full-scale simulation. This chapter also provides an analysis and results of the environment-aware decision process and resulting algorithm selection.

Chapter 7 presents the thesis summary and future research directions.

1.5 Publications

The research conducted and described in this thesis contributed to the following publications:

- Barbosa, P., White, N.M., Harris, N.R. Wireless Sensor Networks for Localised Maritime Monitoring. *IEEE 22nd International Conference on Advanced Information Networking and Applications AINA 2008*, Okinawa, Japan, 25-28 March 2008.
- Barbosa, P., Harris, N. and White, N. Wireless Sensor Networks for Localised Maritime Monitoring. WiSE handout, `http://eprints.ecs.soton.ac.uk/16724/`, 2008.

- Barbosa, P., White, N.M., Harris, N.R. Medium Access Control in Large Scale Clusters for Wireless Sensor Networks. *IEEE 23rd International Conference on Advanced Information Networking and Applications AINA 2009*, Bradford, UK, 26-29 May 2009.

- Barbosa, P., White, N.M., Harris, N.R. Wireless Sensor Networks for Maritime Deployment: Modeling and Simulation. *IEEE 15th Mediterranean Electrotechnical Conference Melecon 2010*, Valletta, Malta, 25-28 April 2010.

- Barbosa, P., White, N.M., Harris, N.R. Design Challenges in Application-Aware Wireless Sensor Networks. *CISTI'2010 - 5ª Conferencia Ibérica de Sistemas y Tecnologías de Información*, Santiago de Compostela, Spain, 16-19 June 2010.

- Barbosa, P., White, N.M., Harris, N.R. Two-Hop Adaptive Routing in Cluster-Based Wireless Sensor Networks. Submitted in *ACM Mobile Computing and Communications Review.*

Chapter 2

Wireless Sensor Networks

This chapter will focus on the general overview of WSNs. The main aim of this thesis involves the networking aspects of WSNs, therefore the network hardware, standards and routing protocols will be covered more in depth.

2.1 Overview of sensor networks

WSNs are formed by nodes that can monitor physical aspects such as temperature, humidity, sound or light. The nodes encompass sensing, processing, communication and an energy source, and can be as small as a few cubic millimetres, such as the Smartdust nodes [34]. By sensing the environment unnoticed, Smartdust approaches the concepts of dust networks and ubiquitous computing [35]. Combining these visions, sensors can be deployed anywhere to collect data without disturbing users unless it becomes strictly necessary. Traditional hardware cannot be used, as size restricts battery capacity, thus device and network lifetime. Instead, WSNs rely on ultra-low power hardware with limited resources to acquire information from the environment and transmit it across the network to an end-user [1].

Due to the restrictions in individual node cost, potential number of devices in use and hardware capabilities, processing and optimising data before a transmission can reduce message size, hence networking requirements and overall energy cost [8]. Indeed, this viewpoint is reinforced by the application-aware and data-centric natures of sensor networks [36]: in WSNs, information retrieval and availability is an essential premise, independently of the application. Data collection and communication strategies will be directly dependent on the scenario demands, influencing the other aspects thereon. For these reasons, research and development starts from specific application demands, and only once these are clear it is possible to identify hardware and protocols.

Three types of devices can be used to form a sensor network: sensing nodes, sink nodes and gateways. *Sensing Nodes*, or simply nodes, are responsible for sensing the environment, gathering and transmitting the resulting data, either with or without local processing. They can also act as intermediates between neighbouring nodes. *Sink Nodes* are structural nodes that can also have network management duties. Sinks gather sensed data and can also manage resources and data flow from sensing nodes, receiving and storing sensed data for further processing. The outcome can then be sent across the network (possibly through other sinks) to other special-purpose nodes called *Gateways*. Gateways may serve both as sinks and external interfaces for the sensor network. Due to their nature, gateways have increased processing power, and often include more than one network protocol and hardware for external interface. WSNs may also include screens for local display of gathered data. According to application, tasks and characteristics of devices used, the requirements for the WSN can change significantly, reflecting on the network device's topology and protocols used. The outcome of these decisions will imply whether or not to use sinks and gateways along with the sensing nodes, as well as the type of interface — if any — to be established with other networks.

Node's hardware basic components and their interaction were described by Akyildiz et al. [1] as shown in figure 2.1. This basic architecture applies to all devices in the network, including structural nodes. There are four basic and three optional components present in each node:

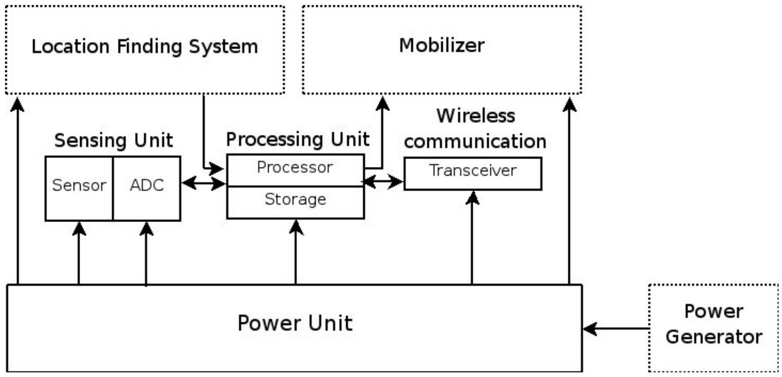

Figure 2.1: Components in a WSN node. Adapted from Akyildiz et al. [1].

Sensing unit. The basic input for any node. Sensing hardware is used to measure temperature, humidity, sound, vibration, acceleration, light, or any other physical aspect, as long as it can comply with node's constrains. Sensed values are converted using Analog-to-Digital Converters (ADC), stored, processed and aggregated locally.

Processing unit. The simplest processors found in WSNs are limited to receive values from ADCs and forward them to other nodes upon minimal processing or aggregation. More advanced processors include complex power management schemes, message encryption, or even complete embedded operating systems. With better processing units, increased memory is particularly helpful for local data storage, resulting in a greater aggregation and reduction of the number of messages for the same amount of collected data.

Transceiver. Responsible for wireless communication between devices, whether optical or Radio Frequency (RF). Part of the network protocol stack is located here. It receives data from the processor and transmits it in standard packets to any nodes in the network. It also receives incoming transmissions, sending the packet message to the processor. Transceivers also deal with the particularities of the communication channel, such as collision and contention.

Power unit. Indispensable in every node, it provides energy to all components. Typically, it comprises a battery and hardware for voltage adjustment. WSN development commonly aims at energy management, more specifically extreme energy savings.

Power generation. Energy harvesting is used to increase node's lifetime. Ideally, they generate enough energy to keep the node running continuously and indefinitely. More realistically, they recharge the power supply to improve network's usability by allowing more samples and transmissions to be carried out without depleting the energy reserves during normal operation.

Location finding system. Although not part of essential hardware in most cases, some applications demand location awareness, hence making this a requirement. Location can either be relative to other nodes or absolute.

Mobiliser. Responsible for physically moving sensors to carry out specific tasks or to maintain a consistent sensing and communication coverage. It is not a common asset due to the power required to operate it.

2.1.1 Application-driven development

WSN's characteristics lead to new application areas and opportunities [8]. WSNs can be used in situations where wired sensing devices could not be used, either due to inaccessible location for cable installation or to the large number of devices required. Implementation speed is another problem of cabled networks that is overcome through wireless communication. For example, deploying a cabled sensor network in a factory requires layout planning and may cause disruption while deploying, whereas a wireless would eliminate these stages. However, the use of wireless communication in small devices leads to concerns over communication robustness and data security [37, 38]. Furthermore, network lifetime is an important issue since nodes rely on their internal power supplies [2].

There are two possible approaches for WSN development, as argued by Raman and Chebrolu [39]: (1) algorithms or protocols and (2) application-centric design. The first approach is abstract, where algorithms are usually considered in isolation from a possible deployment and other node components. The second considers the operation constraints during the development stages. The authors also claim that the bridge between the first and second development approaches are minimal, hence the abstract algorithms are not implemented in real deployments and commercial solutions. As such, deployments are likely to be using simple, non-optimised solutions.

Application-driven development considers both algorithms and application at the same time. Careful balance of parameter's relative importance is a crucial factor for applied WSN development. That is only possible through clear description of the application, such as number of nodes, coverage area, deployment method and obstacles. Starting from this knowledge, algorithms are chosen and implemented, either through simulation or in real nodes, and further optimisation processes can be deducted thereon. The importance of an in-depth description that leads to the best design choices and protocol fine tuning is fundamental to achieve the best solution.

2.2 Network

One of the basic characteristics of WSN is transmitting data reliably between nodes and making it available to external networks and end-users. The limitations described above, such as size and battery lifetime, demand the use of alternatives to proven yet power demanding wireless modules. As such, network hardware plays a fundamental role towards the success of WSN. The the right selection is a trade-off between different parameters, ultimately leading to the balance between power usage and communication robustness. It is also essential that nodes can communicate with each other, independently of the underlying hardware. To guarantee all these requirements, specific ultra-low power network protocols and standards are being introduced.

The most common wireless communication method used in sensor networks is RF. Nevertheless, other types of wireless communication have also been used. Smartdust, for example, used infrared (IR) communication [34]. Infrared hardware requires less power and space than RF transceivers, as the circuitry is simpler. The greatest drawback comes from the fact that infrared is a directed light beam, which demands transmitter and receiver to be in line of sight of each other, making its use impossible through walls and in dusty environments. Ultra Wideband (UWB) impulse radio for WSNs has also been considered before [40, 41]. Comparing with narrowband or spread spectrum RF networks, UWB presents advantages due to lower transmitter complexity (although the receiver is more complex), higher data rate, coexistence with other networks and improved locationing abilities. However, the delays in the standards and the short communication range expected for commercial hardware (theoretically, it has a maximum range of 10 metres) limit its application for WSNs.

RF tasks are essentially to convert a sequence of bits from a micro-controller into radio waves and vice versa. For convenience and practicality purposes, these two tasks are done using one single device, the transceiver. To perform the conversions, the transceiver has different hardware components, such as modulator, demodulator, amplifier and filters. Depending on the protocols, it must be able to select, among others, the communication channel, data coding and transmitting power.

Data transmission can be divided into three different categories [42]: time-driven (or periodic), event-driven and query-driven. Time-driven communication requires nodes to send the gathered information on a timely basis, independently of whether the sensed data is relevant or not. Event-driven transmissions only occur when nodes detect measurements beyond threshold limits, hence sending only valuable data. In query-driven communication, nodes transmit data only upon request from other devices in the network.

To simplify the design, these tasks are divided and assigned into different parts of the network, organised into layers. This process makes the development simpler, as layers can be developed independently and later combined together through interfaces. Due to trade-offs between cost, size and energy available, transceivers are also simplified. This reflects in the protocol stack being simpler than in other wireless devices, exemplified by the reduced number of layers, as can be seen in figure 2.2.

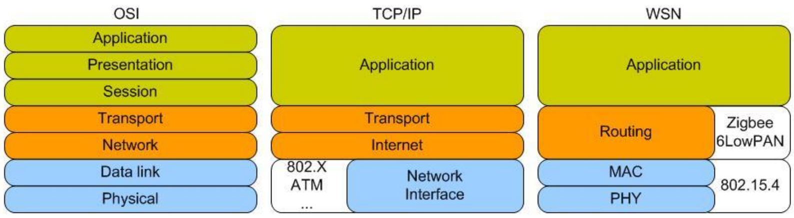

FIGURE 2.2: Comparison of different protocol stacks (OSI, TCP/IP, WSN generic model).

2.2.1 Energy

Wireless communication is the main cause of battery depletion, either while receiving or transmitting data. A typical ultra-low power transceivers require approximately 20 mA to transmit or receive data. Processing tasks requires a fraction of that: as an example, the Telos mote [43], which combines Chipcon CC2420 (standard ultra-low power transceiver) and the Texas Instruments MSP430 microcontroller unit (MCU) (a 25 MHz, 16 bit unit), requires 1.8 mA when processing data with the transceiver switched off. Sensing could also be costly, as shown by Anastasi et al. [44], yet the very low duty cycles (1% or less are common values) reduce the overall power demand.

There are different parts and challenges to communication that will ultimately result in energy consumption variations [45, 46]. Firstly, nodes use a common wireless medium, hence there is channel contention which can result in collision between packets. Furthermore, in case of collisions, nodes may be requested to re-transmit their messages, increasing the energy used per successful delivered packet. At the same time, retransmissions aggravate contention due to the extra packets being sent, particularly in dense networks. To avoid contention and collision, communication schemes create and disseminate schedules to keep the network synchronised. On the other hand, strict schedules only allow limited clock drifting to reduce idle listening and even overhearing messages addressed to other nodes. Therefore, cooperative work is one of the main challenge for energy savings, since nodes rely on a strict sleep and wake-up schedules to avoid information loss due to hardware limitations [47, 48].

Routing protocols and data aggregation mechanisms have been developed to optimise energy savings and communication by transmitting messages through specific routes. These routes are chosen according to pre-defined rules and metrics, such as remaining energy or number of intermediate nodes [49]. Metrics take into consideration the size, displacement, density and communication resources in the network, hence balancing between individual and cooperative interests.

Considering the global energy budget of a network with potentially thousands of sensors, using an ultra-low power device is the best option to achieve reasonable operational costs. As an example, an industrial estate where 100 factories are using a WSN with 1500 nodes each for machine and environment monitoring, making a total of 150,000 nodes. For the sake of argument, only the communication module will be considered. Sensing, processing and different communication modules require a minimum power to operate, yet as most of these components are common to any platform, they will be ignored for the time being. If nodes use standard IEEE 802.11b/g transceivers working continuously, each node will require 100 mW of power while transmitting (a conservative value, since some modules can use over 500 mW), the total energy expenditure for the industrial estate will be 15 kW for the transceivers alone (over 75 kW when considering more powerful alternatives). In contrast, if the transceivers used are ultra-low power, the transmission power is 1 mW, making a total of 150 W (or 750 W) across the estate.

2.2.2 Energy depletion rate

Energy depletion rate reflects on the useful network lifetime. Due to network displacement and routing strategies, energy consumption will vary between nodes. As a comparison, figure 2.3 shows the depletion rate between two networks using single-hop communication and what would be the ideal protocol. When nodes are uniformly distributed and communicate directly with a sink node placed in the geographic centre. In single-hop, peripheral nodes will use more energy for each message transmitted than central ones, when considering that power increases with the square of distance. In the ideal case, the communication load is distributed uniformly across the network, resulting in all nodes becoming depleted simultaneously.

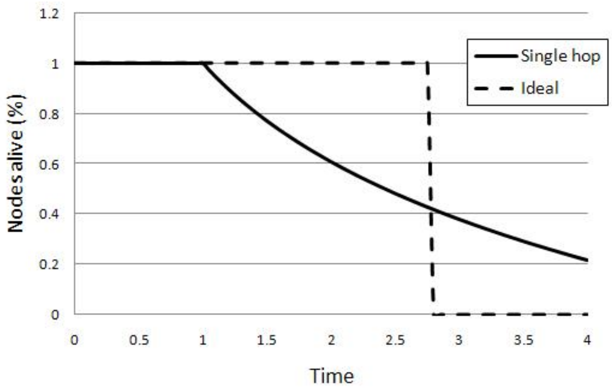

Figure 2.3: Number of nodes alive using simple single-hop routing and the ideal protocol.

Standard WSN transceivers require approximately the same amount of power to transmit and receive data, as can be seen in table 2.1, where the current and voltage required by each module is shown. In fact, some transceivers require more power when receiving than when transmitting. Extended range transceivers, on the other hand, have a transmission power output that can go up to 100 mW. These transmitters allow different operation scenarios and demand different communication strategies to optimise energy usage at network-wide scale.

Manufacturer	**Model**	**Voltage**	T_x **Current**	R_x **Current**
Microchip	MRF24J40	2.4V – 3.6V	22mA	18mA
Ember	EM250 SoC	2.1V – 3.6V	35.5mA	35.5mA
TI/Chipcon	CC2431	2.0V – 3.6V	27mA	27mA
Freescale	MC13201	2.0V – 3.4V	30mA	37mA
RFM	LP2400ER	3.3V – 5.5V	150 mA @ 18dBm	30mA

Table 2.1: voltage and current consumption by standard WSN transceivers [50–54].

Operation	Cycle time	Current	Energy
MCU active	10 ms	1.8 mA	32 μJ
MCU idle	9.7 ms	54.5 μA	1.59 μJ
MCU sleep	963 ms	5.1 μA	14.7 μJ
Tx (0 dB)	10 ms	19.5 mA	585 μJ
Rx	10 ms	21.8 mA	654 μJ
MCU wake-up	6 μs	1.8 mA	32.4 nJ
Radio wake-up	580 μs	20 mA	34.8 μJ

TABLE 2.2: Energy usage for Telos mote using 1% duty cycle, with 3 V supply voltage.

Each node requires at least 4.1 ms to transmit its data when using standard transceiver and maximum packet size (250 kbps and 128 bytes, respectively). In this example, a 10 ms transmission period is used. Table 2.2 provides the energy consumption for the Telos mote [43] when using a 1% duty cycle. The energy breakdown for one period is shown in figure 2.4. The idle time in this example is 1% of the sleep time and the node sends one packet every second.

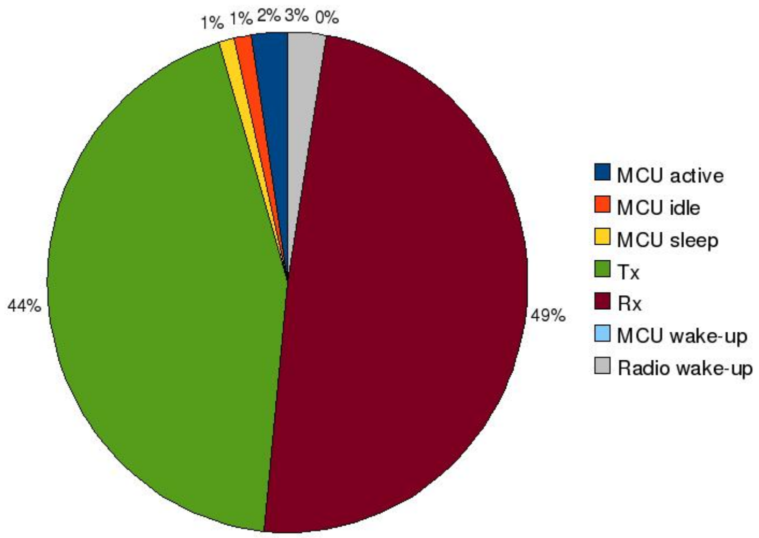

FIGURE 2.4: Energy break for Telos mote.

As shown in table 2.2, the total energy used in one second is approximately 1.32 mJ. If the node is powered by batteries with 20 kJ of stored energy, then a node is operational for 175 days. If the transceiver used is the RFM, the lifetime is reduced to less than 80 days. Should the nodes have their transceivers switched on continuously, the power supply would drain out in less than 11 days with the standard node and approximately 4.5 days using the RFM amplified transceiver.

2.2.3 Connectivity

When a network is deployed it is assumed that it will work correctly, independently of its size or density. Yet, there is a trade-off between set-up parameters: small number of nodes cannot guarantee connectivity in a wide area, while a a densely packed region will be affected by communication interferences, hence reducing connectivity. There are three different types of connecting strategies, as divided by Xue and Kumar [55]: distance-based, number-of-neighbour-based and sector-based. In the distance-based strategy, the nodes transmit using constant power and initially connect to all the nodes within range. The number-of-neighbour-based strategy uses incremental transmission power until connecting to a specific number of nodes. In the sector-based strategy, each node increments its transmission power until it can reach nodes in every sector with angle θ. Whatever the case is, there is the need to optimise connectivity by defining a number of connected nodes from the vicinity, which Xue and Kumar [56] defined as the magic number. This number changed, ranging from three to eight nodes. On the sector-based strategy, the magic number is replaced by θ, which was initially $\theta = 2\pi/3$, and later became $\theta = 5\pi/6$ [55]. These results were based in a uniform distribution where it is guaranteed that there is more than one node in the vicinity.

2.2.4 Latency

Latency can be described as the time between when an event occurs and when it is received by the destination [57]. When origin and destination communicate directly, latency is minimal, as it depends only on channel availability and transmission set-up. When the communication requires intermediates, latency will increase linearly with the number of hops, even for the lightest load [45]. One message can be relayed through several nodes or, in the extreme situation, through every node in the network. In a network with N nodes arranged sequentially (such as in figure 2.5), where each node is able to transmit once every period T, a message generated by node N will need at least $N\,.\,T$ time to travel to the destination.

Latency will also depend on the message generation and transmission rates. The more messages are generated, the less time it will have to forward incoming ones. As all nodes are expected to acquire data from the environment and send it across towards the sink, the delay can grow exponentially. Ultimately, a relay node will not be capable of sending all the messages buffered before another sensing and transmission cycle begins. As such, buffers will get full and messages will be dropped. Therefore, latency depends on the number of nodes, number of hops allowed in the network, transmission cycles and message generation frequency.

Together with energy, latency is one of the most important parameters related to applications and deployment, as stressed by Ruzzelli et al. [58]. Indeed, the two parameters

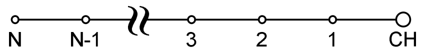

FIGURE 2.5: Nodes arranged in sequence, where each one communicates only with its close neighbours.

are closely related: energy saving techniques such as efficient routing and low duty cycles will increase latency, while latency reduction methods for near real-time retransmission require the nodes to be listening more frequently, increasing energy consumption.

2.2.5 Cross-layer optimisation

Different technologies have different challenges. In the case of WSNs, the best solution to overcome hardware limitations is achieved by optimising individual components and their inter-dependencies simultaneously, as argued by Goldsmith and Wicker [59]. Nodes and network development should be considered in a holistic manner, leading to three main improvements: (1) reduce assumptions of related areas during individual layer development; (2) better combination and balance between individual (node) and distributed (network) aims; and (3) more realistic modelling and simulation during the development stages. Furthermore, Zhang and Cheng [60] outlined four different targets to cross-layer optimisation: improve power efficiency, improve system throughput, fulfil QoS requirements and improve resource efficiency.

2.2.6 IEEE 802.15.4

IEEE 802.15.4 is a standard that specifies the Physical (PHY) and Medium Access Control (MAC) layers for Low-Rate Wireless Personal Area Networks (LR-WPANs) [61]. The standard describes the two lower layers of the protocol stack in terms of data rate, network topology, network address, and power consumption, among other characteristics. It is based on the OSI model and targets low power, low cost, embedded devices without fixed infrastructure. There are two types of devices that can be used: Reduced Function Devices (RFD) and Full Function Device (FFD). FFDs can perform network management tasks such as routing, coordination and network formation, while RFDs are limited to communicate directly with FFDs only.

In terms of topology, 802.15.4 can either operate in star or mesh/peer-to-peer, as shown in figure 2.6. While using a peer-to-peer topology, the network can still form a hybrid topology, since RFDs can only communicate with FFDs, thus creating local, star-like networks. Some of its main features are: packet size is 128 bytes out of which 103 are payload, 64 bit MAC address with provision of 16 bit short addresses and support for

Advanced Encryption Standard (AES) block cipher. The data rates may vary between 20 kbps and 250 kbps and the typical range is 100 metres in open space.

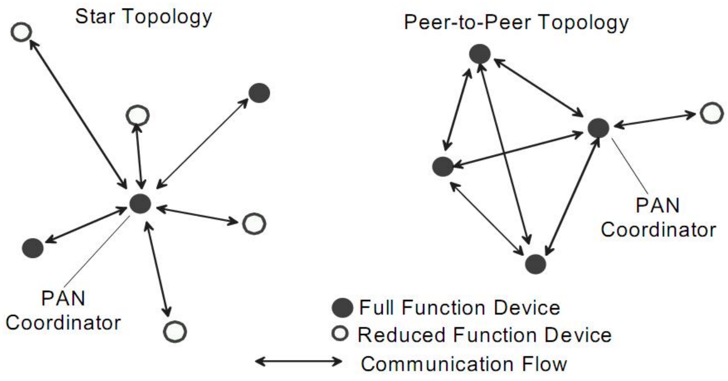

FIGURE 2.6: 802.15.4 star and peer-to-peer topology. Reproduced from [61].

2.2.7 ZigBee

ZigBee protocol [62] is a complement to IEEE 802.15.4 for low power networks. It was created to replace the IP protocol stack over 802.X (WLAN), as this is not aimed at devices with simplified radio. The complete protocol stack is shown in figure 2.7. Like 802.15.4, ZigBee also describes FFDs and RFDs. It supports star, tree and mesh topologies, coordinated by one single FFD. The network can also be extended by using other FFDs as routers. Furthermore, star topologies are the only ones allowing both RFD devices and synchronising beacons. Coordinators are expected to use extended power supply, thus they must either be connected to the mains or have larger power supplies, possibly coupled with energy harvesting hardware.

To make ZigBee as general-purpose as possible, the standard was designed with a profiler. Profiles define the operation environment of the network and allow the creation of interoperable products. Each profile defines the environment of the application, type of devices and cluster used to communicate. The environments defined in profiles can be industrial, domestic, or any other, and they can be either public or private.

A new feature set called ZigBee Pro has been announced in 2007 [63], aimed at larger network sizes with autonomous self-configuration and flexible security. It also allows reports to a single central point, message fragmentation and group addressing.

2.2.8 6LowPAN

6LowPAN provides an IP (Internet Protocol) overlay to WSNs that may be used instead of ZigBee [64–66]. It focuses on creating a compact framework for sensor networks that

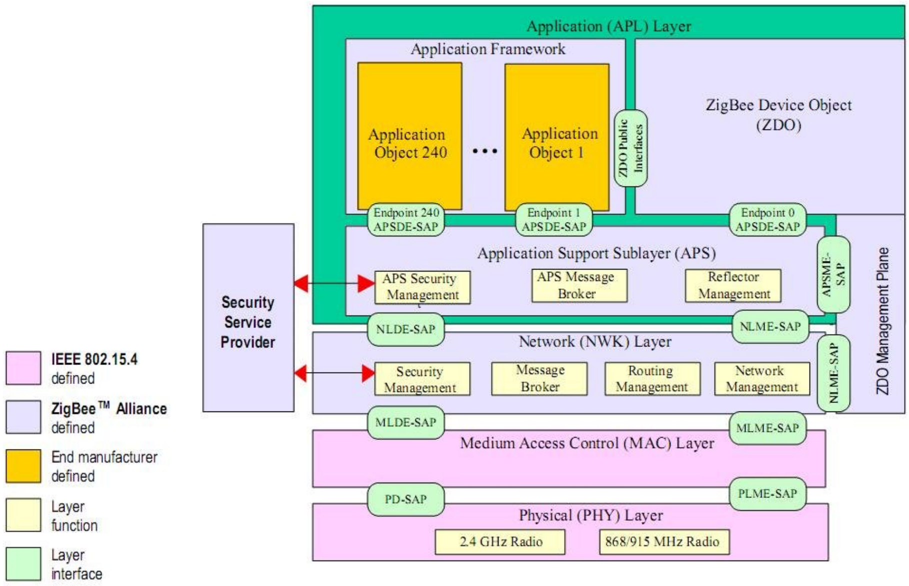

FIGURE 2.7: ZigBee stack over 802.15.4 protocol. Reproduced from [62]

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can provide compatibility with other IP-based networks in a transparent manner. This is achieved by creating an adaptation layer between the IP layer and the 802.15.4 stack. Since the packet size of 802.15.4 is 127 octets (of which 102 are available for payload) and the IPv6 header is 40 octets, a single 802.15.4 packet can encapsulate a full IPv6 packet as a payload and include sensed or any other local data within.

The advantages of using 6LowPAN come from TCP/IP integration, a fully established protocol with a multitude of devices and clearly defined security measures. Comparing with IPv4, IPv6 allows higher node density and may add location-aware addressing techniques. Furthermore, address translation is not necessary, which reduces implementation costs.

2.2.9 Bluetooth Low Energy

Bluetooth Low Energy [67] standard is an ultra-low power variation of Bluetooth standard developed by Nokia and was formerly known as Wibree. The standard is integrated in the Bluetooth stack, and is essentially its variation with fewer options. The main idea behind the low energy solution is to provide Bluetooth with support for devices with limited resources. As such, it targets ultra-low power devices in proximity of a resource-rich device. Due to the common radio, Bluetooth low energy can be implemented in either sigle mode or dual mode, in combination with standard Bluetooth.

Comparing with standard Bluetooth, the low energy version is limited to one power mode, lower data rate (1MB/s), unlimited slaves, 3 frequencies (instead of 32), star-bus topology with no voice capability, and low peak current (below 15mA). Comparing with ZigBee and 6LowPAN, Bluetooth low energy is targeted at small scale networks (although the standard allows unlimited slaves) in a star configuration. The profiles are therefore different and aimed primarily at consumer devices, such as watches, mobile phones and sport equipment. Nevertheless, the addition of encryption provides a basis for more general commercial and industrial development.

2.3 Medium Access Control

MAC layer is the first intermediate with node's hardware (PHY layer), hence it has full awareness of the network's communication aspects. Combining this awareness with one of WSN's main development aim (optimise energy usage) steers MAC's specific development towards the reduction of sources of energy waste [68]: overhearing, collisions, overhead and idle listening. Ideally, nodes wake up to listen to directed packets, with no interferences or collisions, and go to sleep immediately after the transmission finished. Furthermore, the transmission is correctly arranged so that there is no need to exchange control packets between origin and destination, thus reducing overhead. However, this vision is not realistic, and the different issues must be accounted for so that they can be avoided. The proximity with the PHY layer also makes MAC protocols vulnerable to issues with the wireless channel [69]: slow and fast fading, path loss, attenuation, interference, thermal and white noises.

There is a significant number of MAC algorithms developed for WSNs, beyond the standards IEEE 802.15.4, 6LowPAN and Bluetooth previously described. These evolved from three basic access methods [70]: random, slotted and frame based. Balancing network availability with extreme energy savings and simplified hardware creates challenges similar to those found in other wireless networks. Two of the main issues affecting MAC layer are hidden and exposed terminal problems [71]. The example of figure 2.8 describes the hidden terminal problem, where node A is transmitting and node B is receiving. At the same time, node C (unaware of any ongoing communication) also starts transmitting, causing a collision in B. Figure 2.9 exemplifies the exposed terminal problem: node B is transmitting to A, and at the same time C wishes to transmit to D. A is out or reach of C and D is out or reach of B, therefore both A and D can receive packets simultaneously from B and C, respectively. However, since C listened to the channel and detected an ongoing transmission, it decided not to send anything. Both hidden and exposed terminal problems result in less-than-optimal resource usage. Hidden terminal results in collision, hence packets lost and energy waste. On the other hand, exposed terminal leads to channel underuse.

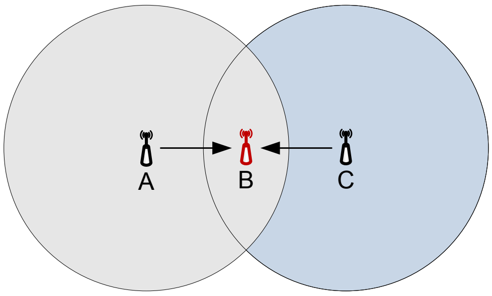


FIGURE 2.8: Hidden terminal problem.

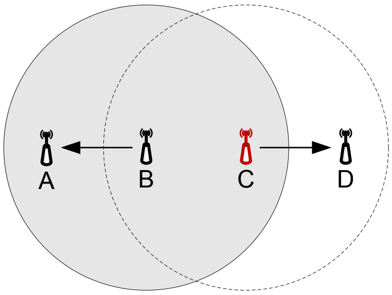


FIGURE 2.9: Exposed terminal problem.

2.3.1 Random assignment protocols

Random access protocols operate in a distributed manner. Each node decides autonomously when to transmit and does so by following general channel access rules established by the different protocols. This provides flexibility to handle different network sizes, since there is no need to decide management strategies prior to the deployment.

ALOHA and slotted ALOHA [72, 73] are two of the first random access protocols developed. With ALOHA nodes transmit new packets immediately. With slotted ALOHA a discrete time slot was introduced, where a node can only send at the beginning of a new time slot. These time slots were globally synchronised and nodes would transmit without knowing if the channel was free or if they risked collision with other transmissions.

Carrier Sense Multiple Access (CSMA) protocols minimise collisions in random access networks by scanning the channel before each transmission for any ongoing communication [74]. Due to the nature of the wireless channel, collision avoidance mechanisms is the most common alternative, as collision detection would demand at least two transceivers (one transmitting and one listening for collisions) operating simultaneously in each node and it is not guaranteed that they can operate correctly. If a collision is sensed, nodes will trigger a back-off algorithm, commonly associated with a delay to the transmission. CSMA eliminates contention between nodes within range of each other, however it does not avoid the hidden terminal problem. Hidden terminal problems are minimised with

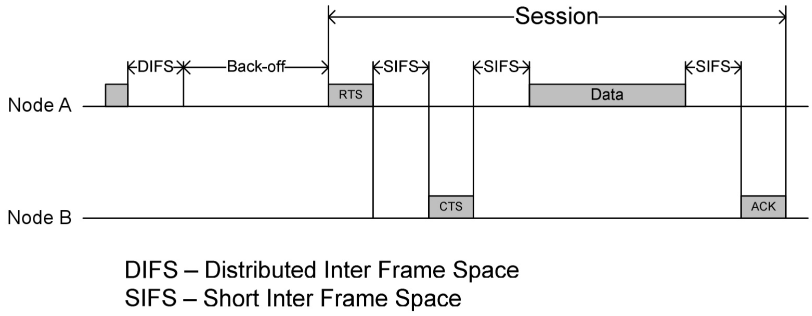


Figure 2.10: Basic RTS/CTS mechanism, where a Short Inter-Frame Space (SIFS) represents the time it takes for nodes to receive, process and transmit frames.

the introduction of handshaking, a mechanism where the origin sends a Request-to-Send packet (RTS) and waits for a Clear-to-Send (CTS) prior to the data transmission. Furthermore, a final Acknowledgement (ACK) message can be sent by the receiver to confirm the correct packet delivery. This procedure is exemplified in figure 2.10, where node A wishes to transmit something to node B. Nevertheless, two new sources of collisions arise from RTS/CTS handshake and lead to message collision [68]: when the origin is out or reach of any ongoing transmission and the destination does not detect the RTS request between two other nodes; and the origin sends its RTS at the same time as another node within range of the destination. These two problems are exemplified in figure 2.11. Another problem with RTS/CTS is the extra overhead caused by the two (or three, with ACK) control packets, since total session time $T_{session}$ is

$$T_{session} = 3 \cdot SIFS + RTS + CTS + DATA + ACK. \tag{2.1}$$

In networks exchanging large packets of data, the overhead is negligible. However, when small packets are exchanged the overhead may become unbearable due to energy and bandwidth usage. This mechanism was initially developed for a single channel and was later improved to on-demand multi-channel [75].

Sensor-MAC (S-MAC) is a general-purpose, energy efficient MAC protocol developed specifically for WSNs [76]. S-MAC reduces the waste of energy by minimising idle listening, overhearing and collisions. To save energy, idle listening is reduced through transceiver duty cycle, trading between energy saving and latency. This creates an extra problem with timing. To overcome this, nodes wake up periodically and scan for any synchronisation (SYNC) packet from other nodes. Being a random distributed protocol using low-cost transceivers, clock drift is expected. As such, nodes receive different synchronisation packets from different sources and decide which neighbourhood to join. S-MAC relies on RTS/CTS scheme to assure that collisions are minimised. To reduce overhead, the RTS/CTS handshake is done once before the first data transmission (when

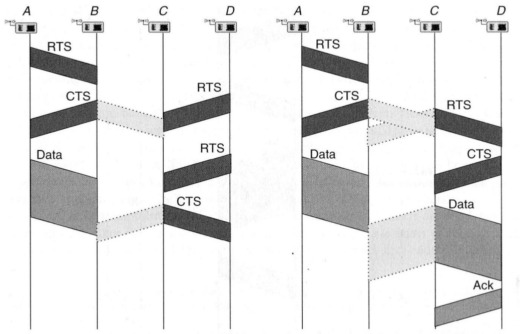


FIGURE 2.11: Two problems in RTS/CTS handshake [68].

a series of consecutive packets is sent between the same origin and destination), however an ACK is still required after each data packet. The RTS/CTS and ACK mechanism also acts as an indicator to all nodes within range the overall duration of the activity. Upon receiving the RTS, nodes set their Network Allocation Vector (NAV) timers according to the time required for the set of frames to be received and correctly acknowledge. NAV can be further extended if a packet is incorrectly sent and repeated afterwards. The complexity of tasks performed by S-MAC make it more than a simple link protocol, and its functionalities extend to network operation and management.

Berkeley-MAC (B-MAC) [77] protocol is the default protocol used in TinyOS, an operating system developed specifically for WSNs [78]. B-MAC was designed to be simple, hence its relies on a small core of functionalities and it doesn't extend beyond link tasks. B-MAC uses Clear Channel Assessment (CCA) for collision avoidance, where each nodes tunes its receiver to assess if the channel is busy or free based on signal strength samples. Nodes wishing to transmit use a CSMA strategy before sending a long preamble. The receiving node wakes up, senses the channel and, if a long preamble is detected, waits for the packet to be transmitted. Furthermore, this scheme does not require synchronisation. The downside of B-MAC comes from using long preambles, resulting in lower channel capacity.

WiseMAC, proposed as part of the WiseNET framework [79], uses non-persistent CSMA with an adaptive preamble preceding the message to overcome clock drift. The nodes have a periodic sleep/wake-up schedule, yet there is no handshaking or ACK to guarantee that the receiver will be ready to receive the packet by the end of the preamble, causing over-emission energy waste. DMAC [80] departs from the observation that networks frequently use unidirectional paths to send the information to sink nodes and create an improved version of slotted ALOHA algorithm. Its main objective is to reduce latency by using a data gathering tree that assigns subsequent slots to nodes in successive data transmission paths. The biggest drawbacks of DMAC are the non-existing collision avoidance method and the extra overhead resulting from the formation of data gathering trees.

2.3.2 Fixed assignment protocols

Fixed assignment divide the resources in a long term manner, where each node has a pre-allocated section for its transmissions [68]. Sections can either be time slots (TDMA), frequency bands (FDMA), coding schemes (CDMA), or a combination of these. To accommodate changes in topology, control packets are exchanged periodically, so the network manager re-distributes the resources. This procedure eliminates collisions. However, their complexity demands resource-rich hardware, making them more suitable for WSN scenarios where at least the network coordinator has more computational power and energy to correctly manage the network. In IEEE 802.15.4 [61], for example, the expected deployments assign a fixed coordinator to manage this task.

The Traffic-Adaptive Medium Access protocol (TRAMA) uses Time Division Multiple Access (TDMA) for energy efficiency [81]. The slot distribution is performed for all nodes within a two-hop range. There are three potential types of access: predicted, random and scheduled. By using TDMA the contention and collision by hidden terminal problems are significantly reduced, resulting in improved energy savings. However, the transmission slots used are seven times longer than the random access period, and the delays are higher than those in contention-based protocols. For these reasons, fixed assignment protocols are more suitable for smaller networks with a steady amount of generated data.

2.3.3 On-demand assignment protocols

In this class of protocols there is a pre-allocation of resources prior to data transmission, on a short term basis [68]. This allocation procedure can be either centralised or distributed. In WSNs this procedure can be found in LEACH, where after each coordinator's rotation there is an immediate re-distribution of the wireless channel between nodes, coordinated by the newly elected CHs [82].

2.4 Routing algorithms and protocols

Sensor networks are usually spread across an area or a region which can vary in size, topology and obstacles. Depending on the topology and deployment characteristics, it may be impossible for all nodes to communicate directly with any destination. As such, the origin needs to find intermediate nodes that can relay its messages towards the destination, independently of their location. This leads to the selection or creation of routing algorithms that allow nodes to select the best path under a given set of conditions.

WSNs differ from other networks, namely Mobile Ad-hoc Networks (MANETs), mostly because of potential number of devices, lack of infrastructure, limited resources, and displacement [83]. In addition, the data-centric and application-awareness of WSNs differentiate them from traditional wired and wireless networks. These factors will reflect directly on routing protocol selection and optimisation.

2.4.1 Protocols division

Due to the increasing number of protocols in WSNs, these were divided according to network structure, operation mode and route discovery [84, 85], as is shown in figure 2.12. To evaluate routing protocols, and independently of that division, there are networking concepts that were either created or adapted to the particular case of WSNs:

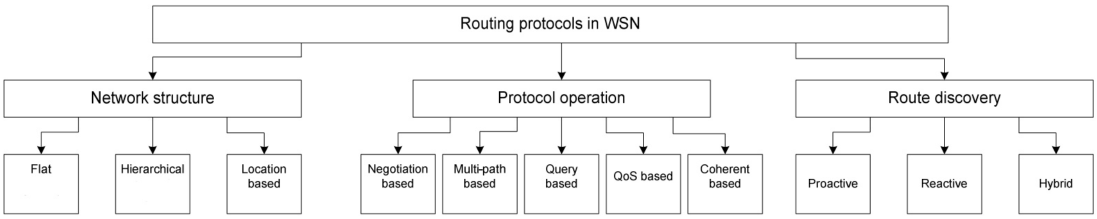


FIGURE 2.12: Routing protocols division.

Single-hop. With single-hop messages are transmitted directly from origin to destination without any intermediate device. This scheme has two main limitations: (1) the increased transmission power required for long distance communication, and (2) the network coverage is limited by the maximum transmission power.

Multi-hop. In multi-hop communication the origin can use intermediate nodes to forward messages to the destination. This scheme can be used to overcome obstacles, increase range or save transmitter's energy. The drawbacks of multi-hop are, as discussed by Zhao and Govindan [86], the increased complexity and collisions, as well as the reduction in packet performance when the network size increases.

Dynamic topologies. Mobility, obstacles, battery depletion and addition of new nodes are a challenge to network protocols. They will influence routing decisions and, ultimately, packet delivery. Dynamic adjustments of network routing and topology are used to minimise the effects of the different obstacles.

Convergence time. The convergence time can be defined as the time it takes for the network to proceed or resume its normal operation. When nodes are deployed on a region a structured network is formed to forward messages between origin and destination. On the other hand, if a node fails to forward its messages, it will search for alternative routes. In these two cases different events trigger recovery mechanisms that eventually result in convergence time.

Event-driven and data-centric. WSNs differ from other networks in their communication focus. Sensing and transmitting data is the most relevant aspect of the concept, therefore addresses can be used solely to identify nodes and manage networks. However, there are cases where bidirectional communication is demanded (sensing and actuation, for example), hence network addressing is required to correctly identify the destination and exchange control messages.

Data aggregation and compression. Once a packet has been received by an intermediate node, and before being forwarded to its destination, it can be processed and combined with the relay's own data, reducing the packet size and number of messages to be transmitted. Moreover, this data can be compressed before transmission to reduce packet size.

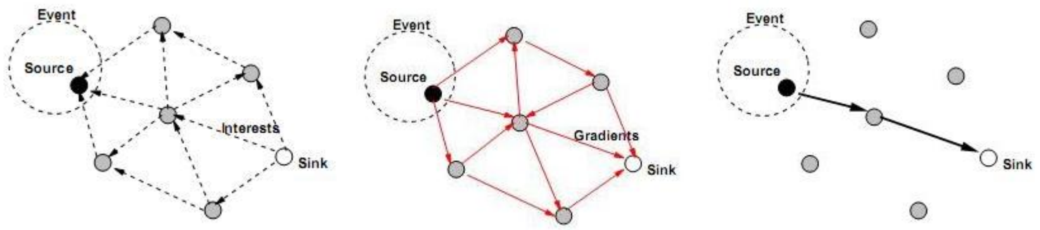
Fault tolerance. If a sensor fails to transmit or gets blocked by any type of interference, it should not affect the network tasks. To that extent, the routing protocol and MAC layer should quickly adjust the transmission power, select different routes or execute any other type of procedure to overcome the failure [84].

Quality of Service (QoS). QoS is commonly related either to communication, energy conservation or both [87]. Furthermore, different applications and requirements lead to different definitions and metrics for QoS.

2.4.2 Flat protocols

The most relevant feature of flat routing is that all nodes have the same role in the network, independently of any hardware difference. Any node can sense, transmit, receive or forward data, depending on location and routing strategies.

The most basic flat routing protocol for WSNs is *Flooding*. It consists of nodes broadcasting once for every new message received. Theoretically, this procedure guarantees that all messages reach their destination, independently of topology, location and obstacles. However, flooding can show a complex behaviour that will reflect on performance, particularly for large size networks. The broadcast storms caused by each event trigger back-off mechanisms and increase the probability of packet collisions [88, 89], thus increasing delays and reducing the number of correct packets being delivered. Furthermore, the redundancy caused by each node transmitting every message received results in low energy savings. Nevertheless, flooding is still a basic technique in ad-hoc protocols, since it allows quick neighbour discovery and convergence time. Another issue with flooding is the complexity at scale that the algorithm shows [90]. Although theoretically the message propagation is epidemic, it is not guaranteed that all nodes will receive it.



(a) Interest propagation (b) Initial gradient set-up (c) Data delivery along reinforced path

FIGURE 2.13: Simplified schematic for directed diffusion. Reproduced from [94].

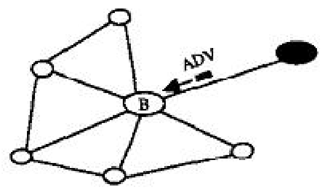
Connectivity radius, link asymmetry and hidden nodes are the main issues affecting the complexity of networks and lead to incomplete broadcasts.

The inefficiency of flooding led to its evolution into *Gossipping*, where each node decides whether to transmit or not a message to one or more randomly selected neighbours. Haas et al. [91] described a gossip algorithm that started by a node broadcasting every new message to all nodes in the vicinity. After that, nodes used a probability function inversely proportional to the hop count. To avoid premature death, the first hops will transmit the message with a probability of 1. This strategy resembles the percolation theory [92], which describes the behaviour of nodes in random graphs.

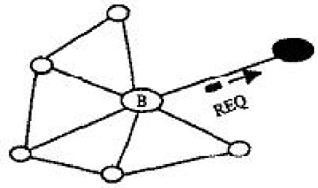
Another evolution of flooding is *Rumor Routing* [93]. It is a compromise between flooding queries and event notifications, where query agents cross the network in search for paths to events, while flooding agents are generated at the event. The paths are created either when the agents reach the destination nodes or cross each other's path. The authors assume two main premises for the development: no geographical information is present and there are no collisions or interferences between transmissions. There is also a compromise between the number of queries, event agents, and their time to live during the set-up phase, where a fine adjustment is needed to provide the best energy saving.

Directed Diffusion, as described by Intanagonwiwat et al. [94], uses data named with an (*attribute, value*) pair to disseminate interests across the network. The interest is first injected into the network by a sink node (figure 2.13(a)), broadcasted hop by hop and renewed periodically. Each node receiving the interest sets up a gradient towards the transmitter (figure 2.13(b)), forming a path from the source back to the sink (figure 2.13(c)). Essentially, a gradient is a reply link characterised by a set of type of data, data rate, duration and interval (or data expiration). Whenever possible, and to save energy, in-network data aggregation is performed by nodes. After the gradient is set, it is possible to repair paths to overcome possible failures and loops.

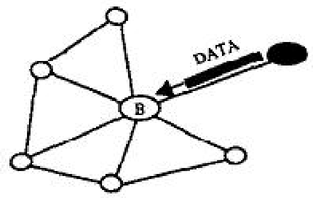
Sensor Protocols for Information via Negotiation (SPIN) is a family of protocols presented by Heinzelman et al. [95]. Unlike directed diffusion, SPIN relies on the principle that every node is a potential sink. As such, nodes negotiate data by advertising it



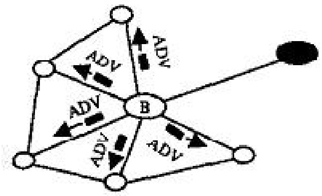
(a) Node B receives data advertisement



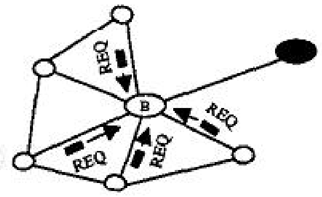
(b) Node B responds by requesting data



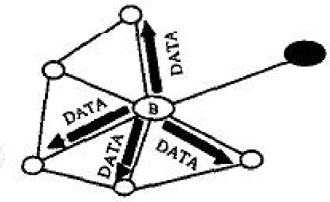
(c) Node B receives data



(d) Node B advertises data to its neighbours



(e) Neighbours request data



(f) Node B transmits data

FIGURE 2.14: The SPIN protocol, reproduced from [95].

through high level descriptors, which are constituted by meta-data associated with the location or the type of sensors. The advertisement is the first of three stages, being the other two the request of data by other nodes receiving the advertisement and the data transmission itself. Figures 2.14(a) to 2.14(f) show a simplified example of the SPIN protocol evolution. Comparing with flooding, SPIN allows energy savings by halving the redundant data, yet it cannot guarantee data delivery to the destination node.

Ad-hoc On-demand Distance Vector (AODV) is a reactive protocol that establishes a route between source and destination upon request and keeps it stored in a routing table [96, 97]. It is based on *Destination Sequenced Distance Vector* (DSDV, which in turn, is based on the Bellman-Ford algorithm) [98], a proactive protocol that, unlike AODV, requires regular updates of node's routing tables. Each node has a routing table with entries to each destination. Although sequence numbers are assigned to each message to avoid loops and improve hop count, they can create problems when establishing new routes due to the risk of message drop for very old sequence numbers. Also, and particularly when nodes are mobile, intermediate nodes may suddenly disappear, causing a disruption in the message route.

Dynamic Source Routing (DSR), like AODV, forms routing on-demand [99]. Unlike AODV, it does not rely on intermediate node's routing table to decide the next hop. Instead, the complete route is decided by the source and attached to the message. This requires each node to store the complete routing path to each destination in its table, making it unsuitable for low memory nodes on large networks. As the protocol is not flexible and routes are not easily updated, it also faces difficulties when the nodes are mobile.

Being created for MANETs, AODV, SPIN and DSR implementations require adjustments so they can operate in WSNs. Firstly, to keep routing tables up to date, more control packets (thus overhead) are needed. On the other hand, if no tables are used all routes have to be set-up on-demand, leading to increased latency. Furthermore, both routing tables and buffered messages require nodes to have sufficient memory to store data.

2.4.3 Hierarchical protocols

Hierarchical routing is used in both wired and wireless networks to improve performance by using point to point communication to the next hierarchical level. Essentially, it consists of dividing the network into layers and attributing different tasks to different nodes and devices, creating a physical and logical hierarchy where nodes in the upper layers coordinate those in the layers below. This coordination can be performed in terms of communication with upper layers, network access mechanisms, energy usage or messages priorities. In addition, addressing becomes simplified and message aggregation can be more aggressive, saving bandwidth and energy [100]. Two other characteristics of hierarchical protocols are described by Al-Karaki and Kamal [84]: first, more nodes can be used as the network is fragmented and addresses can be repeated in different locations (nodes with the same address will be part of different branches); second, higher-energy nodes can be used to receive, process, fuse and transmit data received from nodes in lower hierarchies before communicating with upper levels, improving battery lifetime and optimising processing.

The two types of hierarchical protocols commonly found are based on *Aggregation Tree* (or *Spanning Tree*) and *Clustering*. Spanning tree algorithms create a structured hierarchical tree between nodes (as can be seen in figure 2.15), where one node is the coordinator of the networks and all the others are members. There is at least one global coordinator for each tree, making it the logical root. Its main task is to assign global and local communication schedules optimised to maximise a specific metric (usually the network lifetime). Nodes are identified as being either child nodes or parent nodes, depending on their relative location in the tree. Nodes always have one parent node (their next intermediate towards the coordinator) and can have one or more child nodes (to which they act as the first intermediates). If a node has no child nodes, it can also be called leaf node. Parent nodes can also process messages locally and aggregate their content to reduce the number of transmissions.

Modifications were made to aggregation tree algorithms to bring them closer to WSNs challenges. *Energy-Aware Distributed Aggregation Tree (EADAT)* was introduced by Ding et al. [101]. It uses a greedy probability based on the remaining energy for nodes to start forming an aggregation tree. By calculating how much energy is left, a node v will wait a time $T_v = 1/power_v$ before broadcasting itself. This timer is restarted every

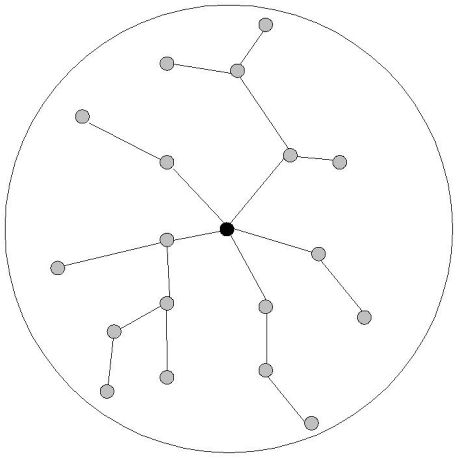


Figure 2.15: Example of spanning tree where one coordinator (black node) controls the connectivity and links between members (grey).

time the node receives an advertisement from a neighbour. Once it reaches zero, the node will broadcast its status. The broadcast message has two purposes: first, allow the vicinity to record v as a potential parent, according to the advertised remaining energy; second, to inform v's parent node about the status change and let the parent change its status to non-leaf node. Although the spanning trees do not need unique global IDs, it is not possible to have two nodes with the same ID within range of each other. Message aggregation mechanisms are used for the network to achieve the best results, especially since the overhead can make structured networks costlier than non-structured ones. Despite the authors' claim that EADAT performs better when the network density increases, simulations do not show results with networks larger than 200 nodes.

More recent approaches, such as the one proposed by Ji et al. [102], aim at balancing the network and finding alternative routes to improve robustness. The authors presented two proposals, both based on the selection of the two parent nodes with lowest weight. In the first algorithm, the node communicates alternately with each parent to improve message delivery. The second algorithm decides by one of the two paths with lowest weight. The weight $w(i, j)$ of transmission a message between nodes i and j is calculated as shown in equation 2.2, based on distance and remaining energy. $D(V_i, V_j)$ is the distance between the two nodes, $E_r(V_i)$ and $E_r(V_j)$ are the remaining energy of nodes i and j, respectively, and k is the system parameter. As this function only takes into account the remaining energy of the current and next step instead of the complete path, it may result in excessive greediness of each node when choosing the next hop.

$$w(i, j) = \frac{D(V_i, V_j)^k}{E_r(V_i).E_r(V_j)}, \tag{2.2}$$

Clustering is seen as the mechanism that can achieve the best scalability [103]. Local coordinators, known as *Cluster Heads (CHs)*, fragment the network into regions or clusters (hence the name). Nodes wishing to join a network interact with the local CH, receiving control messages to schedule their transmissions. CHs also form an upper level (or tier) network with other CHs to exchange data and ultimately send it to one or more base stations (BSs) or sink nodes. BS nodes act as gateway between the WSN and external networks or devices. An example of a three-tier cluster network can be seen in figure 2.16.

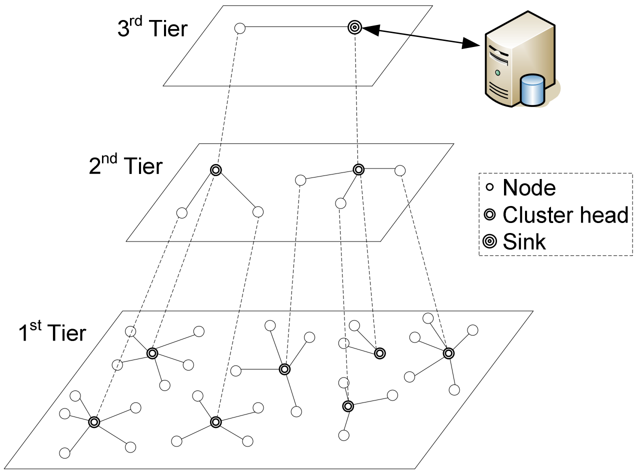


FIGURE 2.16: Example of a three-tier cluster, where the CH of each layer communicates the gathered data across to other CHs and ultimately to the sink node.

Comparing clustering with spanning trees, the fundamental difference has to do with network management. Where spanning trees are managed by one central node, clusters divide the management between CHs, where each one is responsible for maintaining its cluster operational. This strategy assures independence between clusters and decentralises scheduling. As such, each CH acts as an independent agent that receives data from nodes in the cluster, aggregates it and sends it across the network to a sink. The CH also improves the bandwidth usage by aggregating messages and removing local overhead.

Low Energy Adaptive Clustering Hierarchy (LEACH), introduced by Heinzelman et al. [82], was the first clustering algorithm developed specifically for WSNs. The algorithm selects the CHs randomly between all the nodes in the network, acting as local base stations for closer nodes to transmit their data. Considering that the CH is a simple node assigned with additional tasks, it is predictable that its lifetime is reduced, when compared to sensing nodes. For that reason, CH rotation is a fundamental requirement to extend the network lifetime. When a rotation occurs, the new CH will self-elect based on its remaining energy level. Once the CHs are chosen, they will advertise themselves to nodes within their range, allowing them to decide which cluster to join, based on the minimum communication energy. The nodes reply back to the selected CH, which in turn will assign an independent time slot for each one to communicate, in a TDMA manner. Having a specific time slot to transmit data allows nodes to switch off the transceiver while not in use, thus minimising the energy consumption. The energy model used by LEACH to transmit k bits of data over a distance d is:

$$E_{Tx}(k,d) = E_{elec} * k + \epsilon_{amp} * kd^2 \quad (2.3a)$$

$$E_{Rx}(k,d) = E_{elec} * k \quad (2.3b)$$

where E_{elec} is the amount of energy needed by the radio electronics and ϵ_{amp} is the energy needed by the amplifier to transmit each bit. The amplified signal increases with the square of distance is assumed to represent path loss in free space. The values used in the simulation were $E_{elec} = 50nJ/bit$ for both Tx and Rx, and $\epsilon_{amp} = 100pJ/bit/m^2$. It is a relevant fact that, considering a 2000 bit message, these values mean the electronics uses more energy than the amplifier for low values of d^2. When $d^2 = 500$ (approximately 22.4 metres), $E_{elec} = \epsilon_{amp}$, representing the minimum distance when transmission uses at least twice the energy of reception. Assumptions were made when developing LEACH, which led to challenges and problems:

- At least two different MAC protocols are implemented in every sensor. This implies extra computational power and program memory from all the sensor nodes.
- All nodes are within reach of the BS, limiting network size.
- Packet reception is not considered, neither is the set-up overhead that occurs every time a new CH is elected. If these values are too large, the scores achieved are not realistic and the conclusions may not stand true.
- Every node has data to send, and that data can always be correlated to the one gathered from sensor's vicinity.
- There is no topology control when it comes to selecting the next CH. This means that it is possible that the new CHs are not evenly distributed across the network.
- Frequent CH rotation generates large overhead and network disruption, yet it is necessary to avoid premature depletion of elected CHs.
- When an event occurs in one region, there is a broadcast storm that can result in increased energy consumption and packet loss.

To solve the problems of LEACH, further evolutions were proposed. *Power Efficient GAthering in Sensor Information System* (PEGASIS) [104] optimises network lifetime by allowing nodes to communicate with closer neighbours instead of directly with the CH. This avoids the cost of long distance transmissions at the cost of receiving messages in intermediate nodes. PEGASIS showed more than a twofold increase in lifetime over

LEACH, and over 8 times the lifetime achieved with directed diffusion. However, PEGASIS assumed that in order to select the next hop node, nodes must have complete knowledge of both network topology and node's physical location.

Other extensions to clustering were introduced with *Threshold-Sensitive Energy Efficient Protocols* (TEEN) [105] and *Adaptive Periodic TEEN* (APTEEN) [106]. Both algorithms work reactively after the initial clustering set-up. Each node senses the environment continuously and transmits the information to the CH if two criteria are fulfilled: the sensed value is at the same time above a hard threshold limit and differs from the last sent value by an amount equal or greater than a soft threshold. Both hard and soft thresholds are advertised by the CH, which means that in TEEN if the advertisement message is not received by the node, it cannot send any data. In APTEEN, the advertisements are periodic, and it is compulsory for each node to send at least one message during a period of time, even if the hard threshold value was not reached. Also, by establishing a TDMA schedule, broadcast storm issues are dramatically reduced. *Hierarchical TEEN (H-TEEN)* [107] introduces a 4-tier cluster hierarchy to TEEN in order to improve coverage area for small size networks.

A different approach was conducted by Chen et al. [108] with *Span*. The proactive algorithm rotates CHs by electing new ones based on a back-off delay D in each node i calculated using a function $D_i(N_i, T_i, C_i, R)$, composed by the number of neighbours N_i, round-trip delay T_i, number of potential nodes to be connected if i becomes a coordinator C_i, and a random number R. Span tries to guarantee a minimum path when two existing CHs cannot communicate directly or via one or two nodes. As such, the algorithm allows i to become CH in two ways: first, when there is no CH in its vicinity and a random timer reaches zero; second, when i provides a quicker path between two existing CHs. In addition to the CH election mechanism, the decision of not being CH is based on a calculation including the number of neighbours and the round trip mean time.

Further clustering algorithms were developed, as described by Al-Karaki and Kamal [84], Abbasi and Younis [103] and Younis et al. [109]. The increasing number of techniques developed for clustering led to an also increasing number of attributes and nomenclature. Figure 2.17 shows a taxonomy of the different attributes used in clustering of WSNs.

2.4.4 Geographic routing

When nodes have location-enabled hardware, routing algorithms can use it to improve their performance. Locationing can be relative or absolute. Relative locationing is obtained by exchanging information between neighbour nodes and estimating the distance through Time of Flight [110] or Received Signal Strength Indication (RSSI) [111]. Absolute locationing requires *Global Positioning System (GPS)* hardware [112] or any other

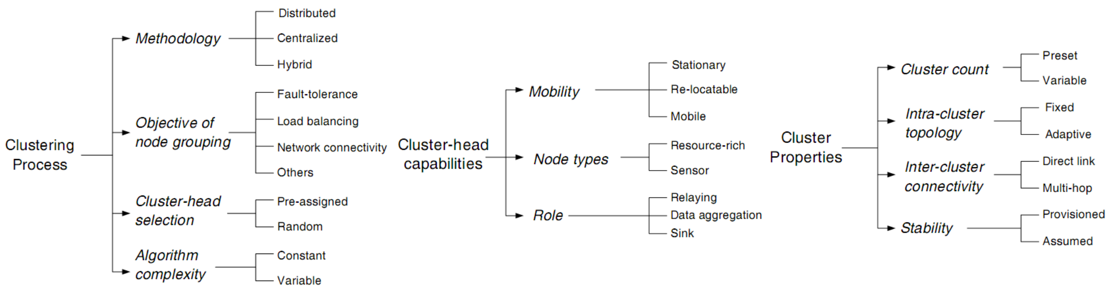


FIGURE 2.17: Cluster taxonomy and attributes, as divided by Abbasi and Younis [103].

that uses fixed reference points. These two methods are part of the range-based localisation schemes. They use point-to-point information to estimate the distance or angle between nodes.

Geographical Adaptive Fidelity (GAF), proposed by Xu et al. [112], does not work entirely as a routing protocol. Instead, it uses the geographical awareness to exploit node redundancy to conserve energy while maintaining network support and fidelity. When a node discovers another one that can maintain the route, they both negotiate which one will handle routing while the other goes into sleep mode. To distribute load balance, nodes are ranked according to their remaining energy levels. After these decisions are made, GAF allows flat routing protocols to run on the network, such as AODV or DSR. *Geographic and Energy Aware Routing (GEAR)*, on the other hand, is an algorithm that uses geographic and energy information to optimise its routing [113]. Nevertheless, if some conditions are noticed, pure geographic routing is chosen to improve message delivery.

There are also the *range-free* localisation schemes, which estimate the distance empirically by understanding single-hop broadcasts and maintaining hop counts to the surrounding nodes. One example of a range-free localisation is APIT, proposed by He et al. [114]. In APIT, a network is formed by heterogeneous devices, some of them equipped with GPS or any other absolute location mechanism. These devices, also called anchors, send beacons to the remaining nodes which, combined with the diameter of the area where the node is, perform an estimation on its location.

2.5 Network modelling and simulation

WSN development is intricate with the system parameters, defined through the envisioned application scenario. The development can then be done by using one of three different methods: analysis techniques, real deployment and simulation. Analysis techniques have had a slow progress untill now [115, 116].

Real deployments have been carried out mainly in environmental monitoring, such as habitat [11], agriculture [10, 117], glaciers [5, 118], volcanos [4], or flood detection [119, 120]. These deployments provide a real testbed for protocols and algorithms. However, the costs involved with deployment and maintenance, the complexity associated with network optimisation and parameter adjustment, and the specificity of each deployment limit the test and analysis of different options.

Simulation is the most widely used method for WSN development. It allows quick development of algorithms and protocol, comparison with different alternatives, analysis, fine tuning and optimisation of complex networks and interactions between nodes. Mathematical formulae based on real deployments or numerical analyses can be used to simulate node's internal processes, as well interactions between devices and environment.

2.5.1 Simulators for WSNs

Network simulation allows quick network set-up, parameter change and network optimisation. It is widely used in wired networks, providing reliable results that mimic protocol's real implementation with high accuracy. The implementations of radio channel and energy models for Mobile Ad-hoc Networks (MANETs) are already accurate enough to provide trustworthy results. With WSNs the low power, low cost, simplified radio hardware used make it more prone to interferences. Furthermore, the accuracy of the simulation is dependent on the level of detail in the implemented models, as discussed by Heidemann et al. [121]. Given the intricacy of algorithm development and energy saving goals, Handy and Timmermann [122] further argue that taking into account battery models with non-linear effects (such as recovery rate and capacity) leads to better optimisation of protocols and algorithms for maximum battery lifetime.

WSN simulators can be grouped in three different categories: custom-built, general-purpose and OS-specific. Custom-built simulators are solutions purposely designed for a particular set of algorithms. They are detailed in the main areas of interest to the particular development and simplified on the other areas. Their advantages are on the detail level of the models essential to the simulations to run. However, the over-simplification of non-essential areas and the highly customised interface and output make it difficult to realistically compare with algorithms developed in other platforms.

General-purpose simulators are flexible and support different algorithms, protocols and environments. Their objective is to provide standard inbuilt models of existing protocols that can be easily customised to fit the demands. The most widely adopted simulator is NS-2 [123], an object-oriented, discrete event simulator originally built for fixed TCP/IP networks. Mobile nodes and wireless network modules were later included, namely IEEE 802.11 and IEEE 802.15.4. NS-2 is built on a free, open-source platform that allows users to develop new modules (such as algorithms, protocols or propagation models) and share them with the community. Its acceptance as a tool for WSN development means that it is possible to find complete implementation of routing algorithms, such as LEACH. The biggest drawbacks arise due to the simplified energy model, overly complex nodes, limited scalability and the potentially distorted results due to the number of modified modules. NS-2 is being replaced with NS-3 [124], however during the writing of this work the latest version did not include WSN extensions. OMNeT++ [125] is a component-based, modular simulator built for wired networks and later incremented with wireless extensions. Like NS-2, OMNeT++ is an open-source, general-purpose simulator with contributions from the community. One of the extensions to OMNeT++ is Castalia [126], specifically built to test WSN algorithms with realistic channel and radio models. OPNET simulator [127] was originally developed for military purposes. It is currently a commercial software, making it less attractive.

TOSSIM [128] is an OS-specific simulator and emulator. It is part of the TinyOS suite and it simulates algorithm implementation over the OS. It replicates the behaviour of a real deployment by replacing the radio and wireless channel by components. The compatibility between TOSSIM and TinyOS means that simulated algorithms can be directly downloaded to sensor nodes supported by TinyOS. COOJA, like TOSSIM, is also an OS-specific simulator, part of the Contiki platform [129]. Other simulators like GloMoSim [130], JSIM [131] Sense [132], or Prowler [133] were also introduced for WSN development. However, the lack of recent versions and the number of publications referencing development with these simulators is minimal.

2.6 Summary

This chapter provides an overview of Wireless Sensor Network state of the art and research trends. Concepts, assumptions and limitations have been introduced and described. WSN's main purpose is to collect and disseminate data, and the paradigm relies strongly on minimising energy consumption while keeping an acceptable performance level. This level is established for each particular case and the unique set of constraints can be derived thereon. The application scenario description and detailed requirements are fundamental to consider and optimise trade-offs between limitations imposed by cost, performance, energy budget, and geographic characteristics of the deployment. Moreover, the set of features is unique to WSNs, qualifying it as an independent research area.

Communication and energy are two fundamental aspects of WSNs. Robust and flexible network protocols where nodes are required to operate correctly during a minimum amount of time for a project to be considered feasible. Furthermore, there are restrictions inherited from the use of simplified hardware that can cause a series of problems and challenges, such as bandwidth availability, message collision and latency.

There are numerous examples of network algorithms and protocols in the literature, some developed targeting a particular application or set of assumptions. In this chapter, an overview of MAC and Routing layers, along with their algorithms and protocols are presented. Routing algorithms differ from each other in network structure, operation and route discovery, while MAC protocols can be divided according to their access mechanism into random, fixed and on-demand. To evaluate these different options, as well as their impact on communication and energy usage, simulators provide an environment where all the algorithms can be tested and their parameters optimised. Although analytical methods and real deployments are also used, the speed and flexibility of simulation environments make it a more flexible approach.

Chapter 3

Medium access in large scale clusters

Chapter 2 provided a description of MAC and routing algorithms, emphasising the need for application-aware design decisions. Considering the maritime monitoring example, the chosen solution must be able to cope with varying network size.

This chapter overviews different MAC options that can be used and discusses what influence they bring to the overall performance in terms of bandwidth usage, energy consumption and latency. Two options are proposed and analysed, following decisions and assumptions based on the application scenario.

3.1 Introduction

As the maritime monitoring example described in section 1.2 suggests, the main aim of the network is to sense and transmit data from nodes to an external entity. To that extent, the network relies on one or more sink nodes capable of gathering the sensed data and communicating with devices outside the WSN. The affected area size can vary significantly. As such, one essential part of the deployment is the capacity of the network to operate independently of size or density. Furthermore, the network must also be able to handle a dynamic topology.

Hierarchical protocols provide methods of dividing the network into different layers with distributed coordination. Moreover, they allow a simplified address management and more aggressive data aggregation. For these reasons, they are the best solutions for variable size networks. Amongst the two hierarchical algorithms described in section 2.4, clustering has the advantage of distributing management tasks across the network through the CHs. As such, it is more flexible to variable topologies. Moreover, as the sea conditions can change dramatically, distributed and localised network management can improve connectivity, which can range from near ideal to very low and irregular.

As previously described, MAC protocols are divided into three main groups: random, fixed and on-demand. Fixed and on-demand have better resource distribution in small scale networks, however managing a large number of nodes in highly dynamic environments leads to increased overhead and causes poorer resource management. Random assignment protocols, on the other hand, are more prone to collisions due to hidden or exposed terminals. Nevertheless, random protocols give nodes a greater autonomy, thus aiding scalability. For these reasons, this chapter will focus on the feasibility of random MAC algorithms in large networks. It is also assumed throughout that, even if clock drift can occur (as it is common in low power, low cost devices), it is not large enough to impact network performance.

In a randomly deployed clustered network, MAC algorithms must be capable of dealing with cluster particularities. There is a degree of freedom in CH deployment, and overlapping between CH ranges is inevitable and necessary, since it guarantees complete coverage. Nodes located in regions overlapping two or more clusters must decide which has the best connectivity and use it alone, while trying to minimise collisions or hidden/exposed terminal issues with non-subscribed clusters.

The aim of this chapter is to provide an insight into the MAC schemes for clustered networks, while addressing the issues and challenges related with maritime deployment. By analysing the performance of different MAC algorithms, conclusions can be drawn about their performance and feasibility. The differences will reflect not only on the number of delivered messages, but also in bandwidth usage, energy needed to deliver those messages and the number of collisions in the network. Ultimately, there is a trade-off between the energy per bit needed to deliver each message and the number of messages that are correctly delivered. Furthermore, as the decision will influence – and be influenced by – the upper network layers, these must be taken into consideration while designing and deciding the best alternative.

3.1.1 Objectives

This chapter provides a study on the behaviour of large scale clusters and discusses the best alternatives for nodes to transmit the sensed information across the network to a sink node. The main purposes of this chapter are:

- To assess the probability of collision in the cluster and, more specifically, of each node.
- To study the need for contention in large scale clusters.

- To study the problem of hidden nodes in a large scale network, how much it will affect communications and whether there is a real need to eliminate it.
- To provide a comparison between the energy consumed by contention-based and contention-free access methods.

3.1.2 Related work

Cluster formation in WSNs has been greatly discussed before. LEACH [82] uses a random rotation process where nodes can self-elect as new CHs. The remaining nodes connect to the closest CH, creating Voronoi cells with the clusters. Bandyopadhyay and Coyle [136] created multiple tier clusters, observing that the energy consumption and convergence time are reduced with the number of layers used. The problem of gateway placement was considered by Aoun and Boutaba [137]. The authors argued that using recursive algorithms that considered latency and energy consumption, along with fewer gateways, did not influence network performance. Conversely, iterative algorithms showed worst and inconsistent performance with variable number of CHs. The Max-Min D-Cluster Algorithm [138] was designed to overcome problems with unbalanced CH distribution and random mobility patterns. It creates sets of clusters where nodes are always a maximum of d hops away from a CH, otherwise they will promote themselves to CHs. However, it does not deal with CH re-election, number of CHs in sparse networks and periodic triggering for CH advertisement/subscription. Wu et al. [139] investigated the construction of a k-Connected m-Dominating Set (kmCDS) using centralised and distributed algorithms. It creates a virtual backbone infrastructure with k connectivity, creating fault tolerance and redundancy. The authors claimed that, although the centralised option achieves a smaller kmCDS, the distributed option is more feasible for a real implementation.

Methley et al. [134] discussed some of the myths about mesh networking. The first myth is that real deployments work as expected in the literature, and even the addition of a new node does not bring additional capacity to the network. In the worst case scenario, new nodes may not even join the existing network. The real advantages of using mesh networks come from the extended coverage and the ability to hop messages when obstacles are compromising connectivity. Nevertheless, as the conclusions refer to flat networks, there is a need to investigate further into these claims regarding hierarchical networks.

Node distribution in algorithm development simulations is commonly assumed to be completely uniform, sometimes with nodes placed in a square grid and with uniform traffic [89, 135]. Real deployments demand nodes to be placed in strategic positions (e.g. on machines, in the case of industrial environments) or by randomly deploying them on a region. In both these cases, the displacement will not be completely uniform and the load sharing will not be evenly distributed.

CLUBS algorithm [140] forms overlapping clusters with three basic requirements: (1) all nodes belong to some group, (2) all groups have the same diameter, and (3) nodes within a group can talk to each other. Each cluster has a 2-hop diameter and relies on broadcasting mechanisms to exchange control messages to advertise and manage each cluster. Overlapping also allows peripheral nodes to subscribe different CHs. CLUBS cannot handle adjacent CHs within range of each other. If that occurs, both clusters collapse and the process is restarted. GS^3, on the other hand, uses a predictable cellular hexagonal structure where CHs are selected according to location [141]. It builds a network starting from a big node (a permanent CH), which elects adjacent small nodes to become CH. The selection process is based on distance between CHs, and ideally these are separated by $\sqrt{3}.R$ from each other, where R is the maximum transmission range.

Fast Local Clustering service (FLOC) algorithm aims at reducing both overlapping and inter-cluster collisions [142]. The node procedure sequence is illustrated in figure 3.1. Each node starts in idle mode and joins a cluster as part of its inner (i_band) or outer band (o_band) once it receives an advertisement from a CH (transitions 1 and 5). If no advertisement to join a cluster is received before a timeout, it becomes a candidate (transition 2), broadcasting its interest. If at least one of its neighbours is part of a cluster, the node drops its advertisement and joins the cluster as an o_band node to avoid conflicts (transition 3). If no conflict is found, the node becomes a CH and advertises its status (transition 4). A node in o_band can join an i_band if a more suitable CH is found (transition 6). The reduced number of clusters lowers the collisions inside each cluster at the cost of unreliable communication from o_band nodes. The reduced number of clusters also reduces the convergence time. The algorithm does not state how inter-cluster communication is performed.

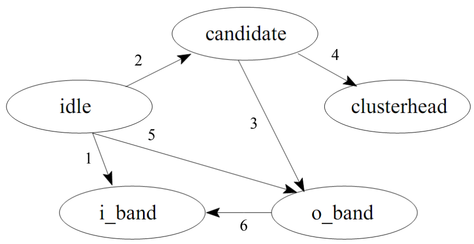


FIGURE 3.1: FLOC state transition. Reproduced from [142].

Unlike the previously mentioned proposals, *Algorithm for Cluster Establishment (ACE)* [143] uses emergent algorithms to improve clustering distribution. Emergent algorithms are localised solutions without global network properties encoded, yet it can emerge through iterative optimisation steps where CHs receive feedback from neighbours to decide which is the best alternative. Due to the iterative process, ACE is robust against node failure and mobility. However, the complexity of ACE makes its implementation and analysis difficult.

3.2 Scalability in wireless sensor networks

Arpacioglu and Haas [144] described scalability of an ad-hoc network as a relationship between parameters change and efficiency. More specifically, scalability refers to the capacity of a network to manage variation in the number of nodes, while keeping the total throughput proportional to that variation. The network performance and scalability constraints is affected by application-specific requirements, as well as the deployment environment. There are two main types of scalability: absolute and weak. The first is an asymptotic result and the second is a result within a finite range. Gupta and Kumar [145] argued that the maximum throughput per node decays as the number of nodes in the network increases. Despite the fact that the types of scalability described by the authors were created for wired networks, there is some parallelism with wireless networks, including WSNs.

Wireless channel has limited bandwidth that must be shared by all users, limiting the maximum number of nodes. As with other wireless networks, it is possible to reuse the bandwidth and channels to improve network usage. On the other hand, the demand for low power and low cost hardware results in limited functionality, reflecting on simpler channel coding and modulation schemes [46, 146]. Aggregation and compression schemes, on the other hand, can help improving bandwidth usage by summarising and reducing data size.

3.2.1 Scalability of other systems and networks

The concept of scalability has been discussed and reviewed before for distributed and parallel computing. Semaphores, Test and Set Locks and other mechanisms are used in computers to avoid sharing regions of memory during critical operations. In multiprocessor systems, the definition of scalability is employed in two manners, as cited by Bondi [147]: the ability of a system to work according to requirements, despite changes in size or performance; and the ability to function as well as take full advantage when the system is re-scaled.

Scalability was further divided into four types by Bondi [147]: load scalability, space scalability, space-time scalability and structural scalability. Load scalability refers to scheduling and exploitation of parallelism with different loads (e.g. number of nodes or transmitting frequency), making the best use of different resources independently of the complexity of assigned tasks. Space scalability takes into account shared resources, such as memory requirements, using methods that avoid system requirements to grow faster than the number of tasks to "intolerable" levels. Space and load scalability are intricate concepts, due to the increased load of available resources when optimising space. Space-time scalability considers the number of objects, applications and data structure's size, regarding their variation to keep a stable and fast operation. It relates to space scalability due to increased storage demands when the number of items increases, as to avoid memory management problems and reduce search times. Structural scalability refers to the implementation or standards and whether it limits or not the number of objects that can be addressed by the system. Apart from load scalability, which can improve its operation by exploiting parallelism and scheduling, scalability concepts are intricate with system design characteristics and standards that can limit changes and expansion. As such, the design stage must consider scalability issues to avoid system-wide limitations.

3.3 Scalability of Clustering Algorithms

Clustering algorithms are theoretically more scalable than flat or other hierarchical approaches. Clusters are physically divided from each other and have independent schedules and management policies, controlled by CHs. As such, the network has a better wireless medium distribution (space scalability) between different clusters. Furthermore, CHs can reduce bandwidth demands though data aggregation and compression when transmitting to the sink node. The CH coordination of subscribed nodes also reduces, distributes and parallelises tasks, when compared with the single coordinator alternative (load scalability). Varying the number of CHs with the number of sensing nodes improves space-time scalability, while correct hardware and protocol selection (along with cross-layer optimisation), and the possibility of node address re-use, improves structural scalability. Clustering also provides higher energy savings. Theoretically, and when compared to non-clustered networks, address distribution and route negotiation can be further simplified, reducing overhead. In practice, the decisions taken while setting up the network will be fundamental to assist this statement.

Having independent tiers and hierarchies allows different routing algorithms in each one. A central issue with clustering is the ratio between CHs and sensing nodes. Increasing the number of clusters reduces the load management in the lower tier, transferring it to upper tiers. Fewer, larger clusters, on the other hand, reduce the network management and overhead in upper tiers, at the cost of increasing contention and collision inside each cluster [148–150].

Cluster management complexity increases with the number of nodes, thus when clusters grow larger end-to-end performance is gradually affected to the point where the network becomes unusable [144]. Network algorithms provide means of improving usability and performance through careful design and adaptation to the application requirements. Considering this, the following assumptions will be used in this chapter:

- An amplified transceiver will be used, extending the node's transmission range and the cluster size. The calculations will assume the same amplified transceiver described in section 2.2.1, with $P_{Tx} = 100mW$ and theoretical 1000 metres maximum estimated range.
- The transmission power increases with the square of the transmission range d, i.e. $P_{Tx} \propto d^2$.

Considering the two assumptions, it is possible to derive the power needed to transmit at range d using 100 mW (0.1 W) transmitter is

$$P_{Tx}(d)[W] = 0.1 \left(\frac{d}{1000} \right)^2 . \tag{3.1}$$

3.3.1 Cluster formation

There are different challenges to the formation of a clustered network, mainly due to deployment and application particularities. First, the existence of one or more sink nodes can influence the CH assignment, whether completely random or epidemic starting from sinks. Second, in heterogeneous networks the CHs can be physically different from sensing nodes (with improved processor and power supply, for example) and be permanently assigned to manage clusters, while in homogeneous networks CH rotation is frequently used to balance energy usage. Third, there is the application itself, which leads to decisions regarding number of nodes, network range, node mobility or maximum number of hops between nodes, CHs and sinks.

The ideal cluster formation would have an uniform CH distribution and transmission range, allowing the creation of a cell-like CH displacement. Figure 3.2 shows an example of an ideal cluster division, where CHs (black circles) are located in such manner that no sensing node (gray dots) is left uncovered. All CHs have the same distance to adjacent CHs and the nodes within one hexagon will subscribe the CH of that region. However, the maritime monitoring scenario predicts nodes and CHs to be thrown from an aeroplane, hence they are not expected to be perfectly located.

Unlike in the algorithms described in 3.1.2, the maritime monitoring solution considers permanent CHs with distinctive hardware. Nevertheless, the same cluster formation process can be applied, indicating where the CHs should be deployed. Combining this decision with an expected margin of error improves CH displacement and overall cluster coverage while minimising overlapping, thus reducing collision and overhearing in intersection areas.

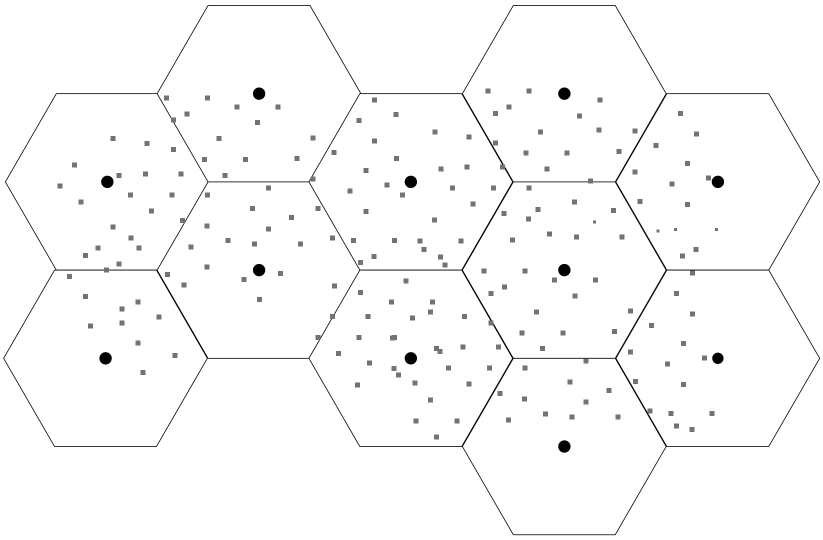


FIGURE 3.2: Ideal cluster division and CH placement.

3.3.2 Large scale clusters

In this chapter it is assumed that the PHY and MAC layers used in IEEE 802.15.4 based amplified transceivers, hence inheriting its characteristics, such as network topologies or packet structure. Increasing cluster size causes MAC challenges: large network performance is affected by increased channel usage, therefore it aggravates the traditional problems found at MAC level. Moreover, large scale clusters limit the protocol selection.

Fixed assignment protocols rely on an arbitrator that indicates which node is going to transmit and when it will do so. This can be done either by polling (only nodes receiving control messages are allowed to transmit) or by dividing the channel into different time slots and nominating nodes for each one. This is done on the set-up phase, during which the CH gets to know the nodes in its range and define specific slots for each one. Both options cause large overhead to maintain the transmission schedule updated and all nodes synchronised. Furthermore, as the network size grows, the complexity of maintaining more nodes and optimising transmission grows also. In contrast, when using random-based protocols nodes can avoid collision by either dividing the channel access into virtual time slots (in a slotted ALOHA manner), listen before transmitting (e.g. CSMA/CA), or using a handshaking procedure (RTS/CTS handshake). With RTS/CTS the decision whether to transmit or not is taken solely by the origin. If contention is detected or the RTS is not succeeded by a CTS, the message origin can either postpone or refrain from transmitting, according to pre-defined rules. If the decision is to postpone, a back-off mechanism is executed and a posterior time decided. Still, handshaking is not flawless, as argued by Xu et al. [151], especially due to large interference range.

There are further important aspects to consider when selecting the channel access mechanism with a limited transmission period [45, 152]:

Energy. Network set-up and overhead increase energy demands. As the overhead grows with the number of nodes, protocols must be designed to minimise this expense and extend operation.

Collision. Transmission and reception are mutually exclusive tasks in a transceiver. As such, nodes can only limit collisions through algorithms design. Additionally, obstacles, multipath, channel asymmetry and noise are problems from the PHY layer that may result in collisions, affecting MAC performance.

Retransmission. When deciding for a later time to retry sending a packet, nodes may be faced with the same problem of contention and collision. This is particularly relevant if the CH demands packets to be transmitted within a maximum time frame, which may cause increased contention at the end of that time.

Redundancy. More nodes mean more complete and accurate coverage. Even if some messages are dropped at times, neighbours can compensate that loss. On the downside, more nodes mean greater chances of contention and collisions.

Overhearing and over-emitting. Ideally, each node only listens to messages destined to it, switching on and off the transceiver for the time it takes to transmit the packet. Over-emitting is caused when a nodes starts transmitting a message before the receiver is ready. Both cases represent energy waste.

Adaptability to changes. Mobility, new nodes within range, and nodes suddenly disappearing will require that the network adapts quickly and effectively to the changes. The adaptability will be reflected in latency, throughput and bandwidth usage.

A trade-off between the above aspects represents a balance between communication reliability, bandwidth and energy usage to better suit each application requirements. In large scale networks, for example, minimising communication overhead has added importance, hence simple protocols gain extra relevance. The aim therefore is to minimise overhead while keeping the data loss low.

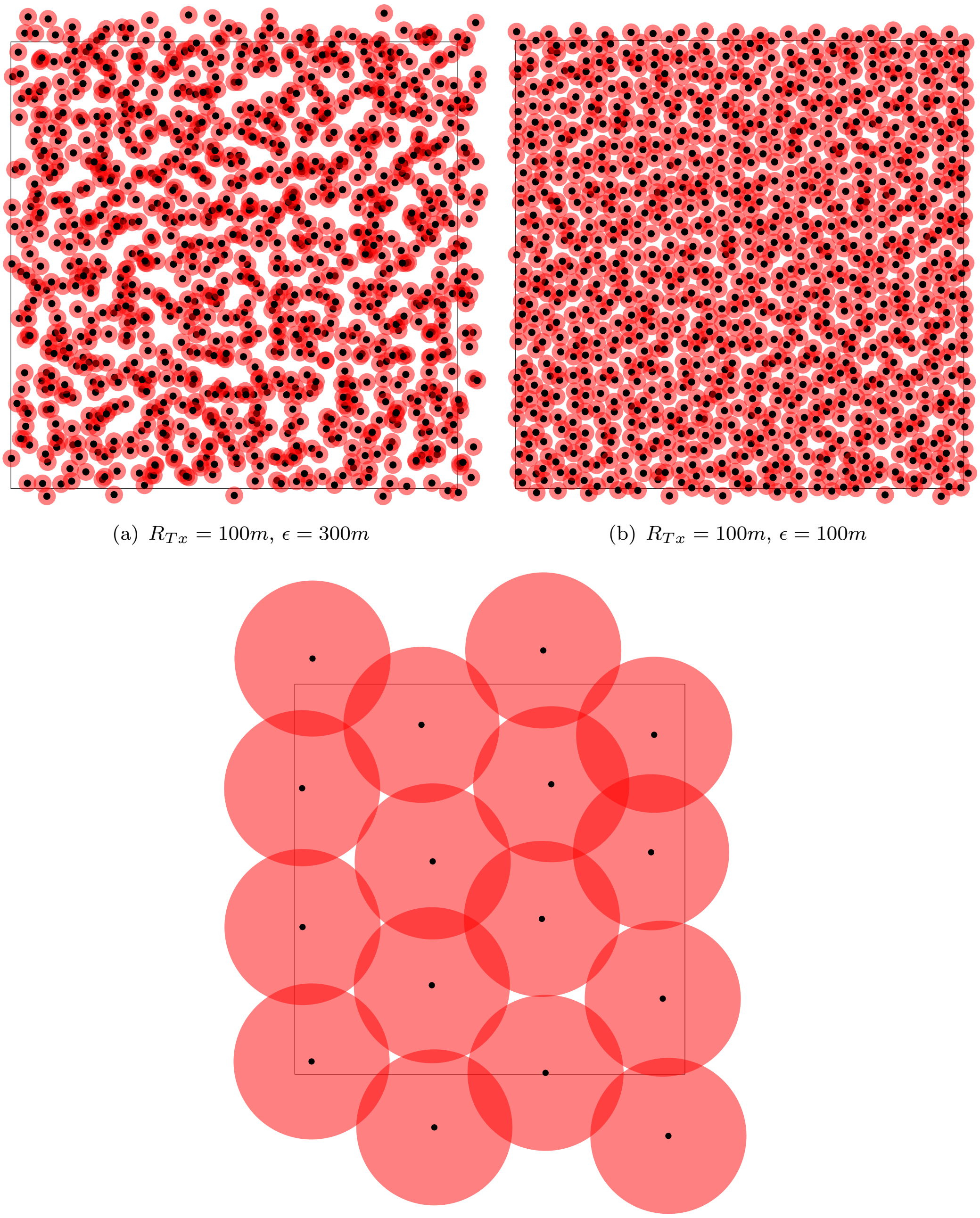
3.3.3 Hardware selection and cluster set-up

Using the scenario described in chapter 1, the network can have as many as one sensor every 100×100 metres area to achieve a resolution comparable to that of SARs. If the size of the area to be sensed is 5000×5000 metres, the network needs 5000 uniformly distributed nodes. Standard IEEE 802.15.4 have a theoretical outdoor transmission range R_{Tx} of 100 metres with $P_{Tx} = 1mW$. If such transceivers are used by nodes and CHs, there would be a high number of clusters where each CH would theoretically control 4 sensor nodes in the described conditions. As a consequence, the network would need a large number of clusters, increasing the complexity of upper tier management. In addition, there is an expected location error from the ideal uniform distribution due to deployment strategy. Figures 3.3(a) and 3.3(b) show two networks where CHs (black dots) with a range $R_{Tx} = 100m$ are deployed to form a cell-like topology. The maximum location errors ϵ are $\epsilon = 100$ and $\epsilon = 300m$, respectively. The CH transmission range is marked with a light red circle and overlapping regions have a darker shade. Both examples show coverage gaps, larger in figure 3.3(b), since $\epsilon = 3 \times R_{Tx}$. If, on the other hand, a long range transmitter is used (with a theoretical $R_{Tx} = 1000m$ for $P_{Tx} = 100mW$), the ratio between R_{Tx} and ϵ will be less penalising. Figure 3.3(c) shows the CH coverage with the same conditions as above (5000×5000 metre area and $\epsilon = 300m$), where CHs use transmitters with $P_{Tx} = 100mW$ transceivers. The number of CHs used is 15, and the coverage is visibly more complete for the same ϵ.

Figure 3.4 shows an example of a random network deployment. It uses the $\sqrt{3}.R_{Tx}$ ideal distance between CHs from a perfect hexagonal cluster, with a maximum deployment error of 150 metres around the ideal location. The deployment consists of 2500 nodes with 1000 metres communication range, randomly deployed in a square area with 7000×7000 metres. The number of sensor nodes used in the figure serves only as example for visibility purposes, where a real deployment is expected to have a denser deployment. CHs are represented by large black dots and their coverage area by red circles. Node (small dots) to CH connectivity is shown with a blue line. To keep overlapping as small as possible, some nodes remained out of reach from any CH. Nevertheless, this can be easily corrected by a routing algorithm that allows outer cluster communication, such as FLOC. Inter-cluster communication is beyond the scope of this research, however if required it can be done either through overlapping nodes or by adding different transceivers to CHs.

3.3.4 Intra-cluster communication

Using transceivers with extended range makes clusters with over 1000 subscribing nodes a possibility. In those conditions, centralised fixed assignment algorithms are unusable or difficult to maintain, at best. Considering the differences described above and the potential nodes within a cluster, this chapter addresses the study of random assignment protocols for large scale cluster communication. As previously mentioned, contention-based mechanisms are prone to collisions due to the decentralised schedule. However, due to their simplicity and lowest impact in bandwidth usage, this work will focus on the analysis and to wich extend collisions and hidden nodes are an issue in large-size clusters, with up to 1000 nodes.



(a) $R_{Tx} = 100m$, $\epsilon = 300m$

(b) $R_{Tx} = 100m$, $\epsilon = 100m$

(c) $R_{Tx} = 1000m$, $\epsilon = 300m$

FIGURE 3.3: Examples of cluster deployment in a 5000×5000 metre area.

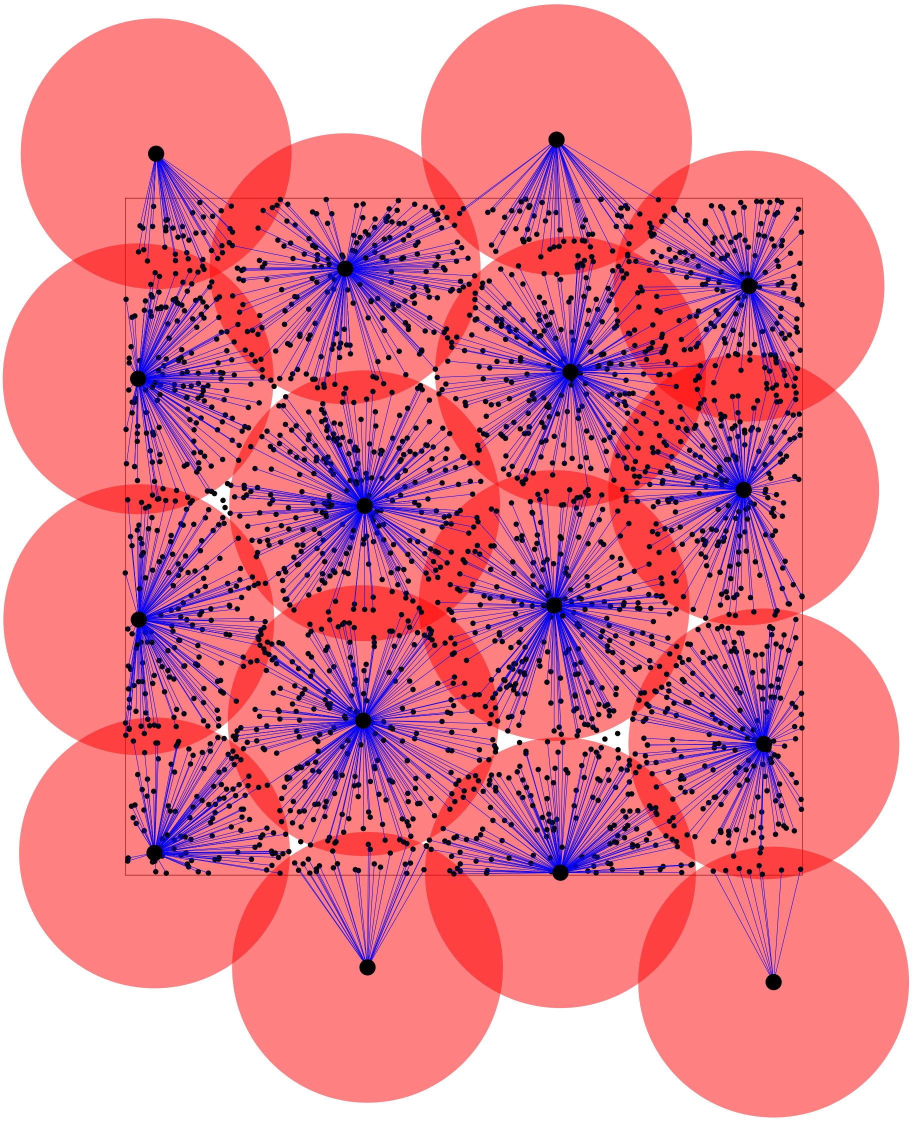


FIGURE 3.4: Deployment example with 2500 sensing nodes in a 5000 × 5000 metre area, $R_{Tx} = 1000m$, $\epsilon = 300m$.

3.4 Collisions and hidden nodes

There is a direct relation between the number of nodes, transmission period and the probability of collisions in a cluster. For that reason, the probability of collision between nodes should be investigated first.

Consider a network of N nodes where $N = \{n_1, n_2, ..., n_k\}$, being k a number between 1 and 1000. Each node requires $t_{Tx} = 10ms$ to send each message (corresponding to more than twice the required to send a $128kB$ packet at $250kbps$). The period of time T that a node has to transmit data varies between 30 and 300 seconds (an empirical value of what the update frequency can be in a real situation), and it is repeated indefinitely. The maximum number of time slots achievable in the super-frame T with these conditions is 3,000 and 30,000 for $T = 30s$ and $T = 300s$, respectively. Each one is able to select its transmission starting time independently (through a random function, for example). It is possible to estimate the probability $p(n)$ of any two or more nodes sending their packets simultaneously, based on the birthday problem [153]. A simplified version of the equation is

$$p(n) \;=\; 1 - e^{-\frac{N(N-1)}{2\tau}} \tag{3.2}$$

where τ is the maximum number of consecutive messages that can be sent without collision, i.e. $\tau = T/t_{Tx}$. The probabilities of having at least one collision for $T = 30s$, $T = 120s$ and $T = 300s$ are as shown in figure 3.5.

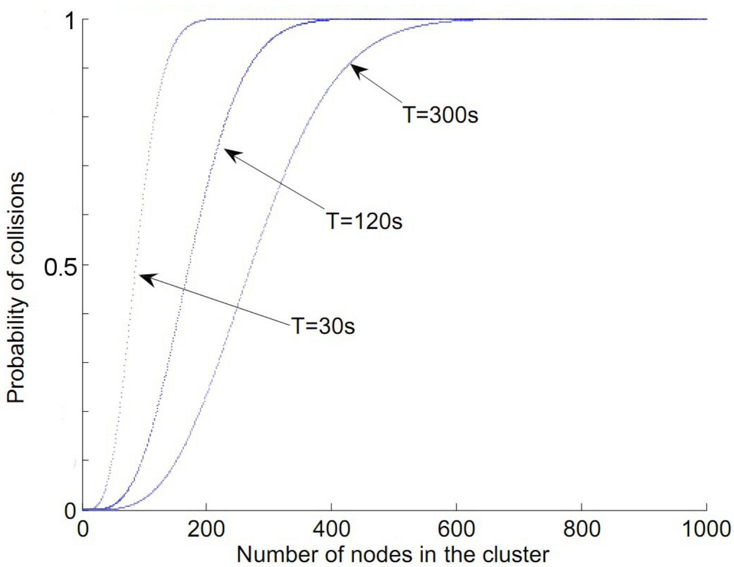


FIGURE 3.5: Probability of any two nodes in the network selecting the same transmission time.

Equation 3.2 shows the probability of collision occurrence between at least two nodes at any time. However, it is not yet clear if a particular node will collide with any other. For a given node n_i, equation 3.3 gives the probability $q(n_i)$ of any other node in the network choosing the same time as n_i, for different network sizes.

$$q(n_i) \;=\; 1 - \left(\frac{\tau - 1}{\tau}\right)^N \tag{3.3}$$

The resulting graph is shown is figure 3.6. The parameters used were the same as in figure 3.5. The number of collisions is proportional to T and N. In a random deployment scenario, cluster size can only be estimated, whereas T is controlled by the CH. As such, adjusting T according to network size is a feasible and realistic solution.

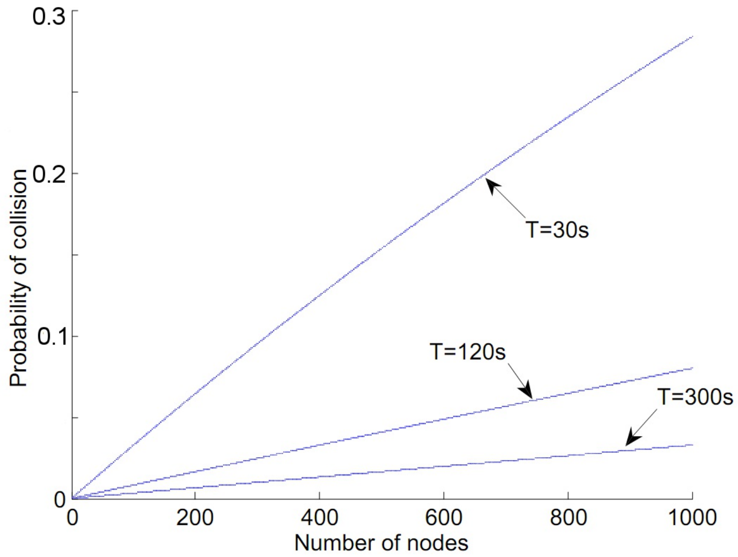


FIGURE 3.6: Probability of any other node selecting the same time slot as n_i.

Medium access mechanisms and collision avoidance schemes are also influential in collision estimation: if collisions can be avoided (for example, by listening to the channel before transmitting), the probability of collision $q_r(n_i)$ is limited to nodes out of transmission range (3.4), where *cov* is the fraction of nodes within reach. Nevertheless, when a handshake process is used, t increases according to eq. 2.1.

$$q_r(n_i) = q(n_i)cov \tag{3.4}$$

It becomes clear that the transmission period must increase exponentially with the number of nodes to keep the same q_r across the network. However, the probability of one single packet colliding increases linearly with the number of nodes for the given network sizes. Hence, it can be said that for a given q_r (i.e. by varying T to achieve the same $p(n)$), individual nodes in a larger network will experience fewer packet losses due to collision.

Case 1: Collision between two or more nodes

Equations 3.2 and 3.3 show the probability of two nodes colliding, given a specific number of time slots. However, it does not show what happens through the entire time. If ρ as the probability of a node selecting a particular time slot, $1 - \rho$ is the inverse probability. Therefore, in a cluster with N nodes, $\rho(n_i)$ is the probability of a given node n_i selecting a specific time (eq. 3.5). The resulting graph for different values of ρ and N is shown in figure 3.7. Using the same principle, figure 3.8 shows the probability of two given nodes using the same time slot if there is a collision avoidance mechanism being used. In this case, nodes briefly listed to the channel before transmitting to avoid collisions.

$$\rho(n_i) \;=\; \rho(1-\rho)^{(N-1)} \tag{3.5}$$

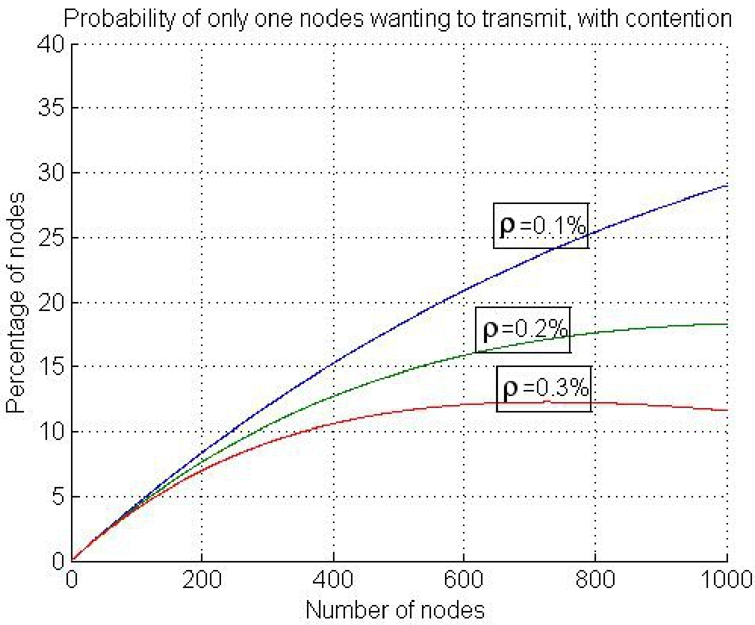


FIGURE 3.7: Probability of collision between two given nodes without collision avoidance.

Case 2: Nodes in the time domain

By having an estimation of the probability of collision and transmission without contention in a network, it is possible to estimate how large clusters behave throughout time. It can be said that if a node n_i transmits successfully at a time slot t_j, it is because it didn't succeed in the previous $t_j - 1$ time slots. Using a geometric distribution, it is possible to estimate how many time slots are needed before node n_i transmits successfully. As before, ρ is the probability of a node transmitting in a given time slot and $1 - \rho$ is the probability of not transmitting in that time slot. As such, for a given time slot t_j, $(1-\rho)^{t_j-1}$ is the probability of n_i not transmitting in the previous $t_j - 1$ time slots. Equation 3.6 gives the probability of each node n_i transmitting in t_j. As part of a network with N nodes, $\rho(t_j)$ should not be considered as an unique event since all nodes face the same probability. The complete independent events at each time slot can be quantified with 3.7.

$$\rho(t_j) \;=\; \rho(1-\rho)^{(t_j-1)} \tag{3.6}$$

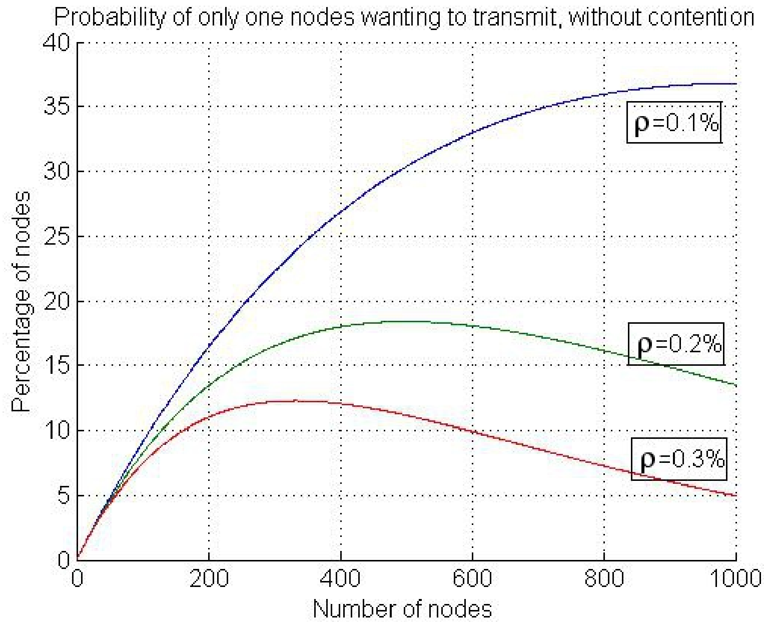


FIGURE 3.8: Probability of collision between two given nodes with collision avoidane.

$$\rho(N, t_j) \;=\; \rho(1-\rho)^{(t_j-1)N} \tag{3.7}$$

For nodes to transmit their data they must first receive a packet from the CH, advertising how long they have to send something. Then each node chooses individually which time slot to use, waiting accordingly. Finally, they follow the implemented MAC procedure to scan for collisions and, if necessary, avoid them. The collision detection is based on the intersection between two circles, where only nodes within the overlapping region and using the same time slot go into contention or collide. If A_{CH} is the cluster area of the CH and A_n is the range of a node n_i, then the probability of detecting any ongoing transmission is given by equation 3.8. Having the intersection of two areas and considering nodes to be uniformly distributed across the network, the probability of other nodes out of range trying to communicate at the same time as n_i is estimated through equation 3.3, where N is a fraction equivalent to the non-overlapping region.

$$\rho_r(t_j) \;=\; \rho.(1-\rho)^{(t-1)} \left(\frac{A_{CH} \cap A_n}{A_{CH}}\right)^N \tag{3.8}$$

3.5 Medium access strategies

When a node decides to transmit its data, it may reduce possible collisions by listening to the channel before the transmission. However, if the improvement in packet delivery is minimal, this advantage might not be relevant enough to justify the extra energy used. To analyse this, a comparison between different medium access mechanisms is presented in this section. Four basic methods of medium access are implemented and compared:

Single try without any channel listening. The simplest MAC strategy where nodes transmit regardless of channel status. This method leads to both maximum number of collisions and highest energy saving (one message sent every time period, without any channel listening), and it provides the basic metrics for collision estimation under the conditions described above.

Single try with channel listening. Using a slotted access with collision avoidance, each node listens to the channel before transmitting. If the channel is being used while listening, the node does not transmit anything during that period of time. The purpose of this method is to have an idea of how much energy can be saved by avoiding collisions with other nodes within range.

Single retransmission mechanism. When detecting a potential collision, nodes postpone their transmission to another time interval and re-select a new transmission time slot. The transmission period is divided in two parts: the first part is used for the initial transmission, while the second is reserved for retransmissions only. With this procedure, retransmitting nodes avoid colliding with regular nodes, while it provides indication of the improvements achievable by using one single retransmission.

Multiple retransmissions. When nodes detect a potential collision, they select a later time within the period. Three different curves will be used to distribute the slot selection probability. This method increases the number of tentatives for each node to send its data at the cost of extra energy consumption.

The simple retransmission mechanism divides the period T in two main sections, T_1 and T_2, as shown in figure 3.9. All nodes try to communicate by randomly choosing a time slot from T_1. If a given node detects any ongoing transmission, it will run a back-off mechanism to choose another time slot from T_2. The distribution of time between T_1 and T_2 can be modified to achieve the best result. In this case, the expected probability of success relies on the success of each time period, where the number of nodes using T_2 will depend solely on a fraction of nodes. If $\rho(T_1)$ and $p(T_2)$ are the probabilities of collision avoidance for each period, then $\rho(T_2)$ will depend on the transmission success and collision rates of $\rho(T_1)$, as the nodes remaining to transmit during T_2 is $N-(N\rho(T_1))$. This probability is also dependent on the transmission range and location of each node and the amount of nodes they can reach from those that communicate with the same CH. Algorithm 1 describes a simplified procedure, where the node resets $currTime$ whenever it receives a new advertisement from the CH. t_{Tx} is the random time slot chosen by the node to send its data The ratio between T_1 and T_2 is fixed. t_1 is the percentage of T

assigned to T_1. After calculating the T_1 and T_2, the node chooses a random time slot t_{Tx} of T_1 to send its data, and will wait until that time slot arrives. If it detects any ongoing transmission, the node will wait another random t_{Tx} that will let it transmit during T_2.

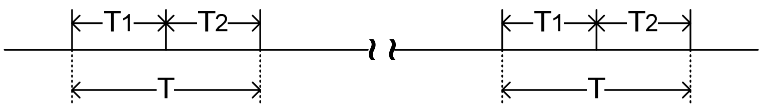


FIGURE 3.9: Single retransmission mechanism based on the division of T into two periods.

Algorithm 1 Time slot division for single retry mechanism.

```
receive T from CH
reset(currTime)
T1 ← t1 T
T2 ← T − T1
tTx ← rand()%T1
wait(tTx)
if channelStatus = free then
    transmitData()
else
    if currTime < T1 then
        tTx ← (T1 − ttx) + rand()%T2
        wait(tTx)
    end if
end if
```

The unlimited retransmission process removes any previous restriction the number of retries allowed in one period, so nodes maximise the remaining time for that period. To assist the time slot selection, a curve fitting model similar to a bell-shaped distribution is carried out by each node. The main objective is to skew time slot selection, making transmissions more frequent on a specific time, while leaving the rest to retransmissions. Figure 3.10 shows a simplified curve fitting model decision. In this model, each node chooses a time based on a probability ρ for each slot. If the selection is made when the period T starts, all times slots are available. If a node decided to use slot t_1 and a collision avoidance mechanism was triggered, it will randomly choose another slot from that moment onwards, adjusting the curve to the remaining time $T - t_1$. To distribute ρ more evenly, when a collision is avoided when $t_1 \geq T/2$, the curve is mirrored to reduce slot congestion. This method is described in algorithm 2. In this algorithm, the node will select transmission time according to the curve model, through another function $curve(currTime, T)$. In the function, a random number is generated and its value weighed according to the curve in use. The objective is to increase retransmissions and packet delivery through concentration of slot selection. The bias towards one particular area of the transmission period results in a greater number of free time slots towards the end of the period. Although energy usage is expected to increase, the retry mechanism is also expected to provide better packet delivery rate than obtainable with a flat distribution.

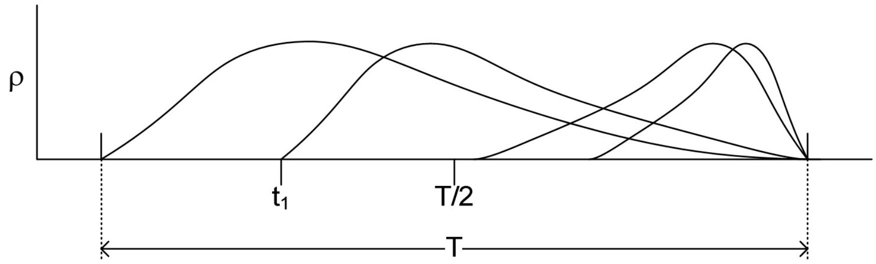


FIGURE 3.10: Multiple retransmission mechanism with skewed curves.

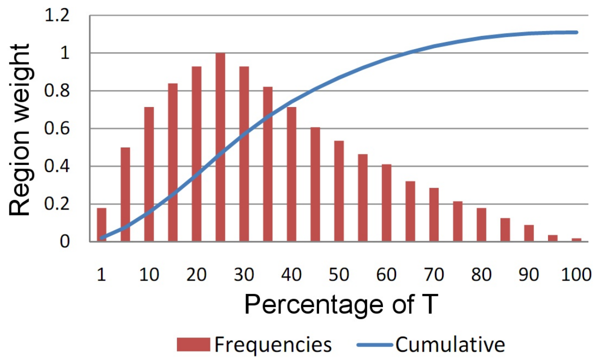
Algorithm 2 Skewed time slot selection with multiple retransmissions.

```
receive T from CH
reset(currTime)
transmitted ← FALSE
while currTime ≤ T and transmitted = FALSE do
  t1 ← curve(currTime, T)
  wait(t1)
  if channelStatus = free then
    transmitData()
    transmitted ← TRUE
  end if
end while
```

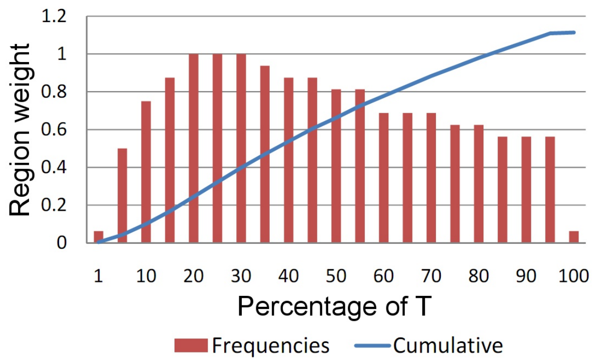
Three different distributions were used for the curve fitting, representing different probabilities of slot selection:

- The first distribution is completely flat, and in practise it is a simple multiple back-off and retry scheme with limited transmission period.
- The second distribution is highly skewed with the maximum at $T/4$ of the remaining time for the first half period ($T/2$), from where the curve becomes mirrored and skewed with maximum at $3/4T$ remaining time. A representation of the distribution can be seen in figure 3.11(a), where the horizontal axis represents the percentage or remaining time (in percentage) and the vertical axis represents the weight that a specific region has on the overall selection.
- The third distribution works similarly to the second, with the highest point at $T/4$ and mirrored from $T/2$ afterwards. The main difference is that the probability of slot selection is flatter, as shown figure 3.11(b).

The algorithms are based in two different variations. The first variation uses nodes transmitting at maximum power, independently of their distance to the CH. In the second, each node transmits using the minimum power for a message to correctly reach the



(a) Curve 1



(b) Curve 2

FIGURE 3.11: Curves used for the probability distribution across the period.

CH. Although in a real deployment the minimum power varies with channel conditions (such as path loss), a transmission power solely based on distance will be used in this chapter.

3.6 Simulations and results

Simulations were conducted to compare the behaviour between different access methods within a cluster. The different proposals implemented represent the adaptation of generic algorithms (such as slotted ALOHA and CSMA/CA) to this limitation, using different back-off and retry mechanisms. On the other hand, the unrestricted retransmission methods were implemented with different curve fitting models to assist time slot selection, in an attempt to improve message delivery. The slot selection process is done using a random number generator. To analyse the energy consumption, the values for each event are based on the RFM LP2400ER transceiver datasheet [54], as described in table 3.1. Furthermore, the propagation time is considered to be instantaneous. Transmission delay is approximately 3.3 μs between two nodes located 1000 metres apart (considering $c = 3 \times 10^8 m/s$), resulting is less than 2% of the Tx/Rx switching time.

Parameter	**Value**	**Units**
Number of nodes	1000	
Number of runs	20	
Advertised Tx time	30	s
Packet size	1024	bits
Transmission time	10	ms
Listening time	300	μ s
Switching Tx/Rx time	192	μ s
I_{Tx}, I_{Rx}, I_{sw}	150, 30, 30	mA

TABLE 3.1: Simulation parameters.

The main objective is to understand how messages collide for a fixed transmission period. Given the expected network density and transceiver range, each cluster can be composed of hundreds of sensor nodes. If, for example, a network has nodes at least every 100 metres (a good approach to SAR resolution), the total number of sensing nodes subscribing a single CH is 314. The simulation considers clusters with 1000 nodes, a conservative value that is expected to generate a greater number of collisions across the network. Moreover, the packet size is fixed at 1024 bits, the maximum with IEEE 802.15.4.

Transmissions start once the CH broadcasts an advertisement packet. In this packet, the CH includes the period length for nodes to send data back. In the simulation runs, the transmission time advertised is 30 seconds. The CH then waits a further 10 seconds before a new advertisement broadcast, to allow any eventual transmission of delayed packets. The listening time before transmitting must be longer than the switching time to avoid nodes missing a transmission while another node is switching the transceiver between Rx and Tx. At the same time it is already longer than the maximum expected clock drift, assumed to be negligible and not affecting channel usage. Nodes are also expected to be able to estimate their distance to the CH. This information is used to vary the transmitting power P_{Tx} to minimise energy usage. At the same time, and because a lower transmitting power results in shorter range, it is possible to understand which effect this option has in collision avoidance.

The results compare successful packet delivery for each strategy, as well as energy efficiency, i.e. the average energy usage per delivered bit. The simulation is divided into two stages. During the first stage three different approaches are studied: transmission without previous listening, transmission with collision avoidance and no back-off mechanism, and the single retransmission mode.

Figure 3.12 shows the different results when each node transmits once and no retry strategy is implemented. Just by listening to the channel before transmitting it is possible to improve message delivery by 8%. It is also relevant to notice that there is a difference between minimum range and maximum transmission range, with the latter delivering nearly 4% more packets. The variation in transmission range affects central nodes within the cluster more significantly, as their P_{Tx} varies from nearly complete cluster coverage to the smallest amongst all nodes, given their distance to the CH. This decision not only improves overall message delivery, but also helps improving energy efficiency: nodes not transmitting will use less energy, and those without transmitting where collisions were avoided will have their packets reaching the destination correctly. Using the values of table 3.1, figure 3.13 provides an estimation of energy usage with the different approaches. As expected, there is an increase in energy from channel listening; however, given the short listening time used, the increase is marginal.

Collision rate estimation is another important aspect of communications. With no channel listening, nodes transmit independently of channel occupation, resulting in 28.5% collision rate. Channel listening reduces this value to 20% and 11.3% for minimum and maximum P_{Tx}, respectively. This means that 1% and 4.5% of nodes did not transmit and they can do it a later times, should a back-off and retry mechanism be implemented.

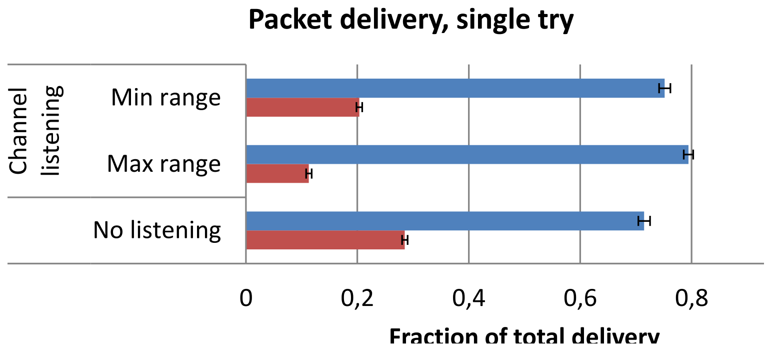


FIGURE 3.12: Packet delivery (blue) and collision (red) for single transmission access methods.

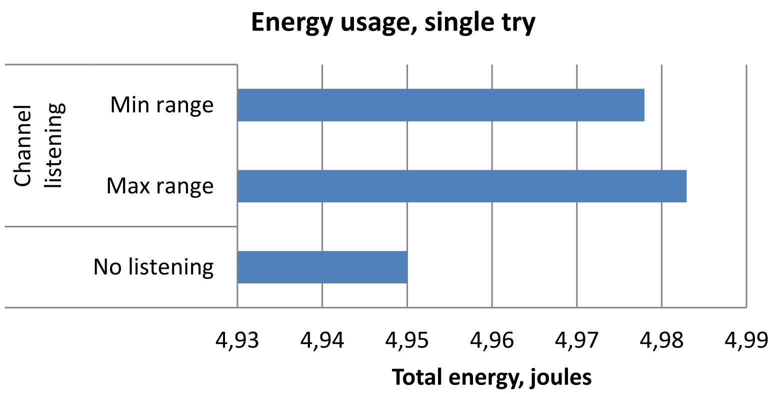


FIGURE 3.13: Energy usage estimation for one period using single transmission access methods.

On the other hand, if energy efficiency is considered, there are significant improvements to be achieved with channel listening. Figure 3.14 shows that with channel listening increases energy efficiency by approximately 10%. More significantly, the use of maximum P_{Tx} shows greater efficiency, due to both the lower number of collisions and greater awareness of any ongoing transmission.

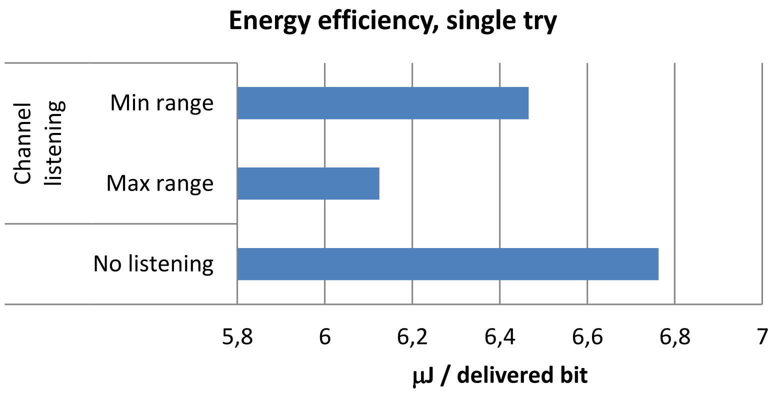


FIGURE 3.14: Energy efficiency for one period using single transmission access methods.

Observing that nearly 80% of the nodes transmit successfully when listening to the channel to avoid collisions, the simple retransmission algorithm periods were divided as $T_1 = 80\%$ of total time, leaving the remaining 20% for T_2. One relevant aspect of this solution is the variation in collision rate due to the change in transmission period, as discussed in section 3.4. If on one hand having independent time frames reduces collisions from retries, it can also increase network congestion during T_1. Figure 3.15 shows the success rate of the algorithm using minimum and maximum P_{Tx}. The time division shows an improvement of 6% for maximum P_{Tx} and 1.4% when P_{Tx} is the minimum when compared to the delivery rates achieved with collision avoidance, no retry options.

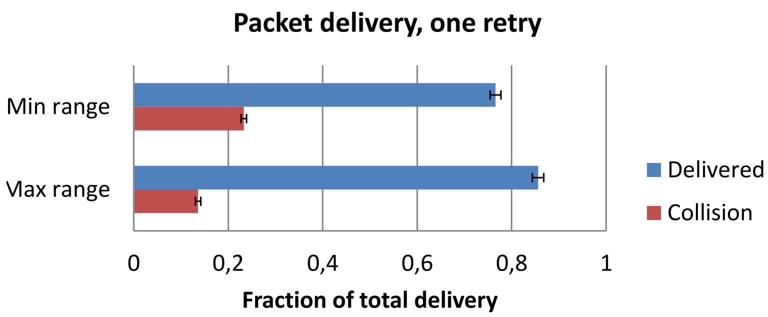


FIGURE 3.15: Packet delivery (blue) and collision (red) for single retransmission mechanism through period division.

The two period option increases overall energy usage, albeit marginally. Nevertheless, there is a significant improvement in energy efficiency (i.e. the energy used to correctly deliver a single bit) derived from the increase in packet delivery, as visible in figure 3.16. With maximum P_{Tx} the energy usage drops to 5.7 μJ/bit, 7.6% lower than the singe try option.

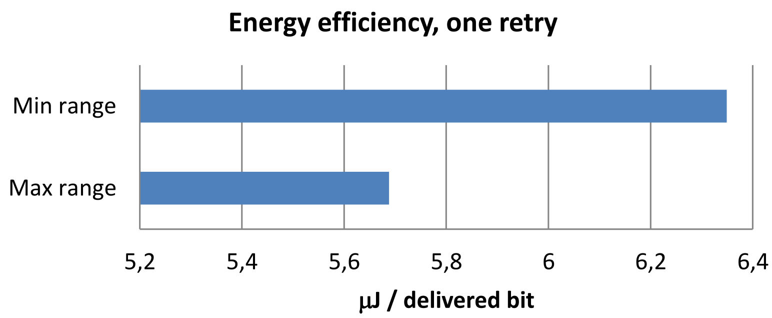


FIGURE 3.16: Energy efficiency for retransmission mechanism through period division.

The curve fitting model aim is to bias the slot selection to specific times, increasing contention, back-off and retries at the cost of lower energy efficiency. The table in figure 3.17 provides the results of the multiple retransmission with two different curves (displayed in figure 3.11). Results show that flatter curves increase delivery rate, opposing the initial expectations. The smaller concentration of transmissions in one area reduces the probability of collisions. With maximum P_{Tx} the collision rate lowers from 17% with the highly skewed alternative, down to 14% with flat distribution. Moreover, the number of nodes retransmitting is smaller when using a flat distribution. Out of the three alternatives, the flat distribution is the only one achieving better delivery rate than the single retransmission scheme, by 0.4%. This increase is mainly due to nodes retrying successive retries until the channel is free. Like the other MAC options, multiple retry also shows a higher energy efficiency when P_{Tx} is maximum, as visible in figure 3.18, being over 10% for a flat slot selection scheme.

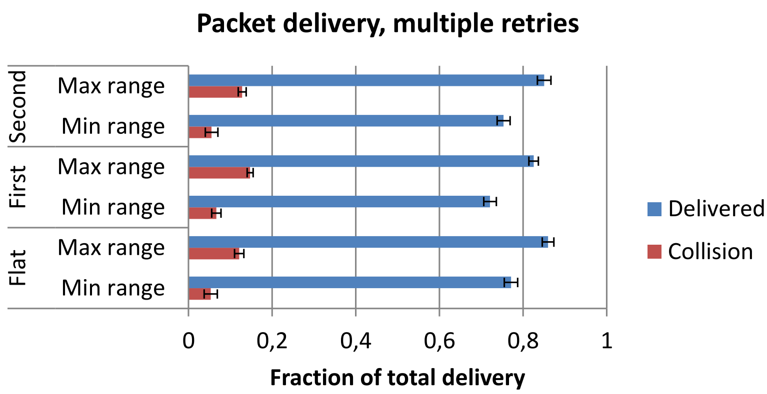


FIGURE 3.17: Packet delivery (blue) and collision (red) for multiple retry with curve fitting model.

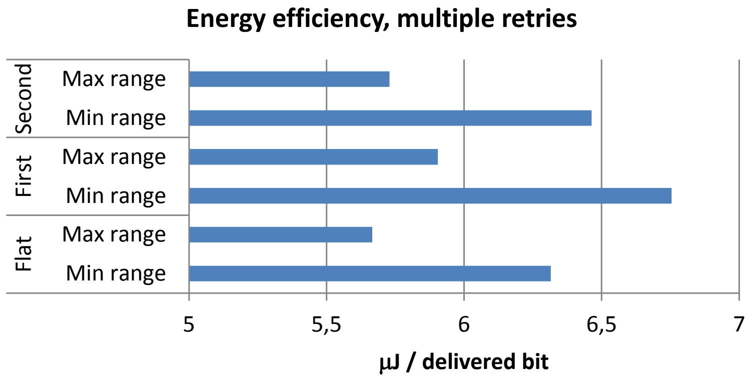


FIGURE 3.18: Energy efficiency for multiple retry with curve fitting.

3.7 Discussion

This chapter presented collision estimation in large-scale clusters. Between the different options implemented, even simple contention mechanisms without any retransmission can be very successful. The simplest schemes showed over 70% packet delivery rate, while keeping the energy usage lower. Choosing random over fixed assignment protocols allows higher collisions from hidden nodes. Moreover, the lack of coordination leads to a greater bandwidth waste. On the other hand, the network gains flexibility which, considering the potential number of nodes, is an advantage.

Comparing the theoretical estimations with the results obtained, the network behaviour is predictable, as are the number of collisions. In theory, a network with 1000 nodes using 30 seconds for transmissions each node has 30% probability of collision. The simulations showed that, under the same conditions, a transmission without collision avoidance has 28.5% collision rate between packets, increasing to 29% if the standard deviation is considered. The period selection was kept constant for comparison purposes. As the collision rate was close to the theoretical estimation, the greatest variation is expected to come from displacement changes, and it will be tested with a full cluster implementation.

Channel listening improves energy efficiency over the simple transmission strategies for two reasons. First, if nodes do not transmit, their only expense is channel listening. Second, by avoiding collisions, the number of delivered packets increases. Multiple retry schemes show the greatest energy consumption between the proposed alternatives. Moreover, the cost of delivering each bit is the lowest with simple channel listening. From the simulations it also becomes clear that the use of maximum P_{Tx} achieves the best delivery rate, compared to minimum P_{Tx}. The energy efficiency is also improved, despite the greater transmitting power. This difference affects mainly nodes closer to the CH, since the shorter transmission range increases the number of hidden nodes, hence collisions.

Among the most successful algorithms, the two-period retransmission with maximum P_{Tx} represents the best trade-off between packet delivery and energy efficiency. On the other hand, multiple retransmission scheme allows greater delivery which, despite the lower efficiency, is still an advantage when successful packet delivery is the ultimate goal.

3.8 Summary

Wireless communication is associated with the highest energy usage by sensor nodes and ultimately by the whole network. Medium Access Control is part of the network stack, hence part of the optimisation challenge. The issues related to packet delivery are often hidden from the upper layers. Retransmissions, if occurring, are handled by the MAC layer and only the final result is sent upwards. As result, and in order to achieve the best compromise, the first challenge to protocol development is the optimisation of PHY and MAC layers.

This chapter focused on the medium access problem in large-scale clusters, how it influences the energy consumption and the message delivery rate. The use of clearly outlined transmission periods (in a slotted CSMA manner) represents a realistic approach to environments where mobility and periodic obstacles limit the time nodes are allowed to transmit packets successfully.

Chapter 4

Cluster routing

One common assumption concerning communication and node lifetime is that multi-hop routing proposals are better than single-hop schemes, as short range communication reduces energy usage and improves channel efficiency. Chapter 3 describes the challenges that MAC layer algorithms face in large scale clusters. The results were obtained by using single-hop routing inside the cluster. Considering the claims found in literature that multi-hop allows greater energy savings (as described in chapter 2), this chapter provides an analysis of whether relaying messages is an alternative to single-hop. Results will focus on energy usage, message delivery and latency.

4.1 Introduction

One of the main research aims in WSNs is to improve energy efficiency by optimizing hardware and communication between nodes [2, 59]. Due to the application-aware and data centric nature of WSNs, energy conservation is important to guarantee an extended network lifetime. At the same time, it must also achieve a minimum overall performance, as specified by the upper network layers [36].

The development of new routing algorithms and protocols is frequently based on the assumption that by avoiding long range single-hop transmissions it is possible to reduce energy usage, even when origin and destination nodes are within range of each other. Routing algorithms provide mechanisms and rules to relay messages through other nodes between them, in a multi-hop manner. To support this assumption, the inverse square law states that transmission power increases with the square of distance in open space communication, therefore relaying one message through at least one node in between origin and destination should allow energy saving. However, the ultra-low power transceivers require approximately the same amount of power to transmit with maximum strength and receive packets. As such, multi-hop may lose its advantage over single-hop due to the additional transmissions and receptions required to complete the relaying.

In this chapter, single-hop and two-hop routing schemes are studied and compared. Two-hop routing is the simplest multi-hop scheme, hence it can demonstrate if energy savings can be achieved, when compared to transmitting directly the destination. Furthermore, location is evaluated to understand how energy usage is distributed between origin and intermediate nodes. The theoretical findings lead to the development of two-hop algorithms that take advantage of network displacement to save energy. They also use the knowledge of remaining energy and distance to the receiver in order to identify which route is the most advantageous. The first approach concentrates entirely on the least costly route, while the second one balances the load through different routes to avoid overloading one of them. This chapter is a progression towards efficient multi-hop schemes. Due to the assumed simplicity and limited processing abilities of the nodes, the developed algorithms must also be simple enough to guarantee a successful implementation. A simulation was then created to evaluate and compare the theoretical findings.

4.1.1 Objectives

There are three main objectives to this chapter:

- Estimate energy consumption using single-hop and two-hop communication.
- Analyse the regions where energy savings are possible and how nodes can use and take advantage of this information.
- Evaluate the implications of multi-hop in packet delivery rate and latency.

4.1.2 Assumptions

The following constraints and assumptions will be used throughout the rest of the chapter:

- All nodes are displaced within transmission range of the CH, even if they relay messages through intermediates.
- In a typical node operation, communication is responsible for over 90% of the energy consumption in the node, thus the energy needed by the other components present in the node will be neglected.

- The main focus of this chapter is to understand the Routing layer-related aspects. MAC and PHY layers are assumed to be working optimally, thus the issues associated with their implementation are not considered.
- Clusters are independent from each other and with no interference from any external source.
- No aggregation or compression schemes are used. As such, each node must transmit once for every received or generated message. Although this decision affects the energy consumption and message delay of the transmitting node, it also allows the transmitting node to use all the message payload for its own collected data.
- The network is composed of a large number of nodes randomly deployed and its lifetime is described as the operating time in which at least 90% of the initial nodes is still operating.
- Nodes have locationing hardware (such as GPS), therefore they can estimate their relative position to other nodes in the cluster.

4.1.3 Related work

Routing is a recurrent subject in WSN research, as mentioned by Al-Karaki and Kamal [84]. Surveys on clustering were presented by Abbasi and Younis [103] and Younis et al. [109], where this approach is considered the most popular for large-scale networks. Clustering was compared to non-clustered networks by Vlajic and Xia [148], with the authors suggesting that, despite common belief, clusters only present advantages over other types of networks when they are formed by nodes with highly correlated data, and where all nodes are within two hops of a CH. Nevertheless, the assumptions are based on highly flexible networks with no fixed cluster head.

Among clustering protocols, a two-hop strategy was used by Liu and Liu [154], showing improvements over chain based and energy-aware protocols. In their approach, the authors used local meshes where one node (assigned by the base station) sends the collected data across to other meshes. This mesh head (or CH) rotates frequently to avoid early depletion of its power supply. Nodes inside a pre-determined range communicate directly, while nodes outside that range use the closest relay available. This algorithm raises three concerns: (1) the mesh head rotation causes excessive overhead, especially if it is distant to the base station and intermediates are needed; (2) peripheral nodes in each mesh will act on self-interest, increasing the number of hops, delays and energy usage for each message; and (3) each mesh does not provide means of distributing energy consumption across, while the base station bases its decisions solely on remaining energy, therefore it becomes difficult to expect a uniform energy consumption across the network.

Bjornemo et al. [155] argued that even two-hops are worse than single-hop with regards to energy consumption. The comparison is done using a single relay to transmit data from a determined number of nodes with no aggregation. Furthermore, the authors argue that the overall impact of message aggregation is marginal, and even the impact of greater transmission power for single-hop – and its interference – does not affect the results significantly. The authors also claim that hierarchical network structures with single-hop strategy can be beneficial. These results were obtained with transceivers that have the same receiving and transmitting power, limiting their scope.

Conserving energy is one of the main objectives of clustering. In this case, node distribution and traffic routing schemes can provide not only overall energy usage reduction, but also more uniform consumption. Adaptation of the Bellman-Ford algorithm can be found in Chang and Tassiulas [156], Kansal and Srivastava [157] and Karp and Kung [158]. These algorithms compute directed graphs which attribute weights (usually energy or distance) to different paths. If a path is used more often than another, its weight will increase, thus the intermediate node will have less energy. The sender will then choose a lighter path, distributing messages more evenly. Nevertheless, this solution does not take into account the distance between sender and receiver, hence a solution that combines remaining energy with transmission distance can potentially provide better results.

4.2 Energy usage in WSNs

There are two major advantages of using multi-hop routing in WSNs: increase coverage and improve energy savings. In this section, energy usage and savings are investigated. To that extent, two different generic options for the transceivers are considered: the first option uses a transceiver that requires the same amount of power to transmit and receive data, while the second uses a long-range transceiver, where the transmitting power is five times greater than the receiving power. This decision is justified since some applications (such as large-scale maritime monitoring) can benefit from longer transmission ranges to increase cluster size and reduce complexity in upper tiers. Given the theoretical power required to transmit and receive messages, the energy usage is analysed on both single node and complete route level. Furthermore, in the case of relaying, the ideal location of the relay node is estimated, as well as the areas where there is a potential benefit from using it.

4.2.1 Single-hop vs. Multi-hop

To improve energy distribution inside a cluster, it is first necessary to understand if multi-hop routing has real advantage over single-hop. To do so, a node displacement such as the one in figure 4.1 is considered. In the figure, node X is within the maximum

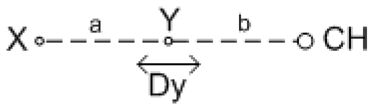


FIGURE 4.1: Distance between three nodes.

transmission range of the CH, and must use maximum P_{Tx} to send its messages correctly. Node Y is between X and CH, and it can be freely moved to adjust distances a and b between nodes. Node X has two possibilities of sending a message to CH directly or through Y (two-hop). For the sake of argument, it is considered that Tx and Rx are the only two tasks consuming energy in the node. Moreover, it is assumed that the nodes are using isotropic antennas, and that the path loss is given by equation 4.1, where d is the distance between sender and receiver, f is the frequency, c is the speed of light in vacuum, and η is the path loss exponent, with values typically between 2 (free-space) and 4 (relatively lossy environment). It is also assumed that the maximum P_{Tx} is the same as the receiving power P_{Rx}, and that the CH is a resource-rich node that can operate continuously during the network lifetime. If d_n is the maximum transmission distance of a node n, then $P_{Tx} \propto d_n^\eta$. As $4\pi f c^{-1}$ is a constant due to system losses, the transmission loss will depend on η and d. In this example, it is considered that the transmission is performed in free space, hence the path loss is constant. As such, the transmission power can be simplified to $P_{Tx} = d_n^2$.

$$L_p = \left(\frac{4\pi df}{c}\right)^\eta \tag{4.1}$$

Case 1: $P_{Tx} = P_{Rx}$

When using standard IEEE 802.15.4 low-power transceivers, the receiver usually requires approximately the same power as the transmitter. Considering as an example the topology of figure 4.1, the distance between X and the CH is $e = a + b$, and total transmission power needed to send a message from each node to the CH in single-hop (P_{sh}) is

$$\begin{aligned} P_{sh} &= P_X + P_Y \\ &= e^2 + b^2 \,. \end{aligned} \tag{4.2}$$

On the other hand, if the messages are sent in multi-hop manner where node X relays its messages through Y, then Y will receive one message and send two to the CH, as no message aggregation scheme is being used. As the power needed by Y to receive a message is the same as P_{Txmax}, then it can be said that $P_{Rx} = e^2$. As such, the total power needed for multi-hop P_{mh} is

$$\begin{aligned} P_{mh} &= P_{XY} + 2.P_Y + P_{Rx} \\ &= a^2 + 2.b^2 + e^2 \, . \end{aligned} \tag{4.3}$$

In order to be an alternative to single-hop, multi-hop must use less power overall. This means that P_{sh} must be greater than P_{mh}. As such, equations 4.2 and 4.3 can be compared, resulting in

$$\begin{aligned} P_{sh} &> P_{mh} \\ e^2 + b^2 &> a^2 + 2.b^2 + e^2 \, . \end{aligned} \tag{4.4}$$

There is no solution to this equation for any position of Y between X and CH (considering $b < e$, P_{mh} will always be greater than P_{sh}).

Case 2: $P_{Tx} > P_{Rx}$

Although ultra-low power transceivers are common in WSNs due to energy savings, they are not the only alternative. Their limited range may not be sufficient for some applications, making long range transceivers with improved Signal-to-Noise Ratio (SNR) a better option. The main difference between standard and long-range transceivers is the ratio between P_{Tx} and P_{Rx}, where transmission requires a greater amount of power than reception. For that reason, $P_{Tx} = gP_{Rx}$ will be considered, where g is the ratio between transmitting and receiving power. By changing eq. 4.3 and still assuming that $P_{Tx} = d^2$, it becomes

$$\begin{aligned} P_{mh} &= P_{XY} + 2P_Y + P_{Rx} \\ &= a^2 + 2b^2 + \frac{e^2}{g} \, . \end{aligned} \tag{4.5}$$

As such, eq. 4.4 can also be modified to obtain g:

$$\begin{aligned} P_{sh} &> P_{mh} \\ e^2 + b^2 &> a^2 + 2.b^2 + \frac{e^2}{g} \\ g &> -\frac{e^2}{2ab} \, . \end{aligned} \tag{4.6}$$

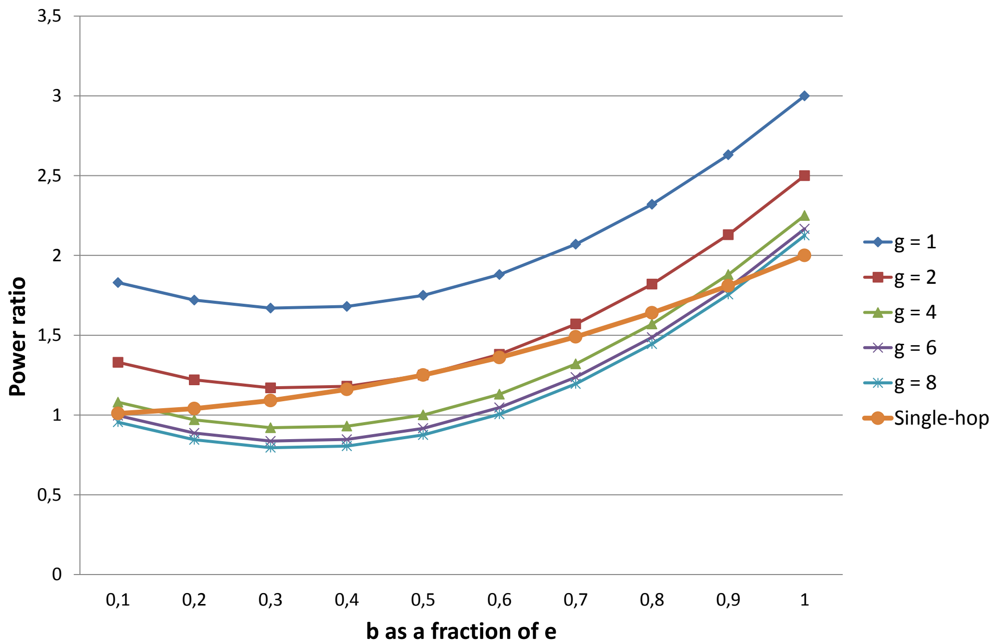


FIGURE 4.2: Total power required by nodes to send one message each to CH using single-hop and multi-hop with different transceiver gains, where 1 corresponds to the power required for a single transmission.

Differentiating eq. 4.6 with respect to b (e is a constant), the ideal location for node Y in respect to X and CH can be estimated for the lowest total powers:

$$\begin{aligned} \frac{d}{db}\frac{-e^2}{2b\,(b-e)} &= 0 \\ \frac{-e^2\,(4b-2e)}{(2b\,(b-e))^2} &= 0 \\ e &= 2b. \end{aligned} \tag{4.7}$$

As eq. 4.7 shows, when the relay node is precisely halfway between the origin and the CH (i.e. when $a = b$), the sum of powers used to send that message is the smallest possible. If nodes X and Y are placed in these locations, multi-hop is an energy saving alternative for any $g > 2$. Figure 4.2 shows the power needed to transmit two messages (one from each node) to the CH using different values for g ($P_{Rx} = P_{Tx}/g$). Single-hop total power is used for comparison, when moving node Y between C and CH. Multi-hop will allow energy savings in areas below the single-hop line. From the figure, it is visible that if $g = 1$ there is no improvement from using relays, and even when $g = 2$ there is only one location where the powers are similar. On the other hand, significant saving can be achieved if $g > 2$, although only when the relay node is within specific regions.

Depending on the difference between maximum P_{Tx} and P_{Rx}, the ideal position of Y will change and different energy savings can be achieved. In addition, when deploying nodes randomly, the probability of having a node exactly in the middle of the path between

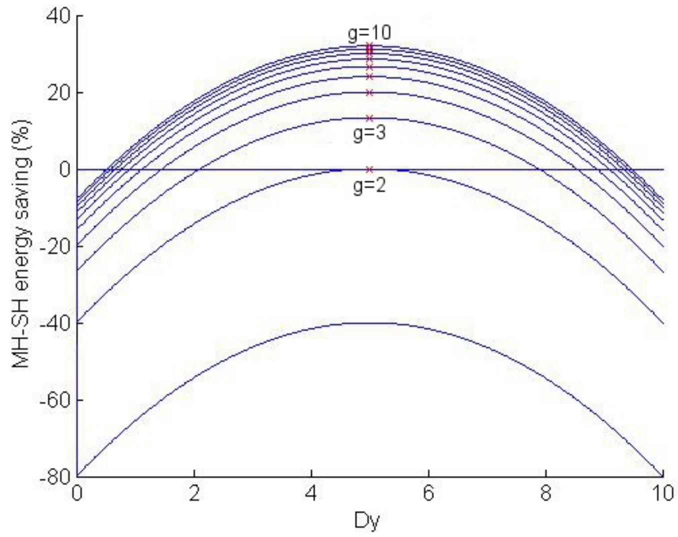


FIGURE 4.3: Energy saving ratio between multi-hop and single-hop for different Y location and g values when $/eta = 2$.

X and CH is low. For that reason, figure 4.3 shows the region where multi-hop allows energy savings over single-hop, and how much energy can be saved.

Having $\eta = 2$ is an optimal condition. In real deployments, the path loss exponent can be greater than 3. Figures 4.4 and 4.5 show the energy saving when η is 3 and 4, respectively. It is noticeable that while the point of maximum energy saving remains the same, single-hop is still a better alternative when $P_{Tx} \approx P_{Rx}$. However, the value of g where single-hop and multi-hop use the same power for the different values of η changes, becoming $g = 1.3(3)$ and $g = 1.14$ for $\eta = 3$ and $\eta = 4$, respectively.

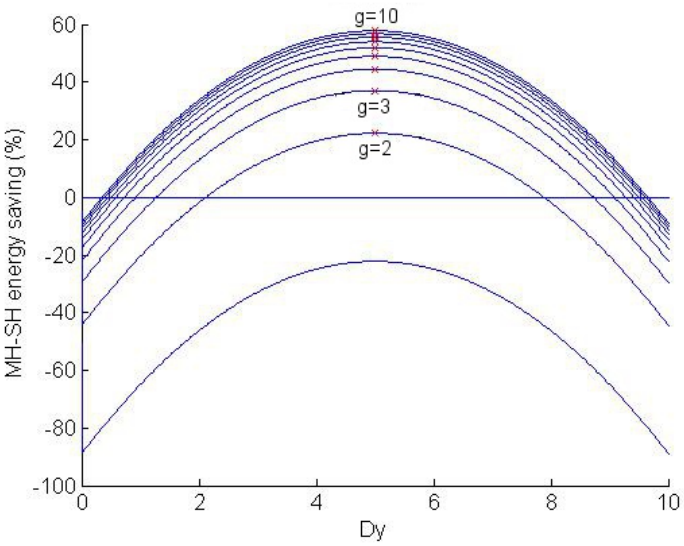


FIGURE 4.4: Energy saving ratio between multi-hop and single-hop for different Y location and g values when $/eta = 3$.

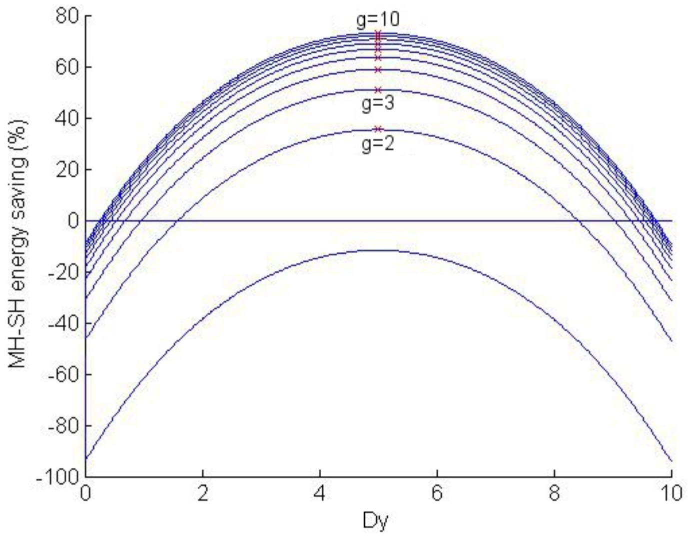


FIGURE 4.5: Energy saving ratio between multi-hop and single-hop for different Y location and g values when $/eta = 4$.

4.2.2 Energy distribution

As previously described, multi-hop routing can reduce energy consumption across the route as a whole. However, it is not yet clear how the energy consumption is distributed between intervening nodes. Depending on the location of Y, the transmission power distribution will also change. If node Y is closer to X than it is to the CH, it will transmit twice the messages at a longer range, therefore it is expected to use more energy than X during each cycle. If, on the other hand, Y moves closer to the CH, X will continuously increase its transmitting power. At some point, the total energy used by X will be greater than that of Y.

Ideally, all nodes in the network should consume the same amount of energy, so that they have a similar depletion rate. This is only possible with multi-hop, by balancing message relaying, whereas single-hop does not allow any balancing scheme. If E_X is the energy used by X during a transmission period, and E_Y is the energy used by Y during the same time, it is possible to derive the ideal node location for $E_X = E_Y$. Assuming $t_{Tx} = t_{Rx}$, E_X and E_Y become:

$$
\begin{aligned}
E_X &= E_Y \\
P_{Txx} &= P_{Rxy} + 2P_{Txy} \\
a^2 &= \frac{e^2}{g} + 2b^2 \\
b &= \frac{-2g + 2\sqrt{-g + 2g^2}}{2g} e
\end{aligned}
\tag{4.8}
$$

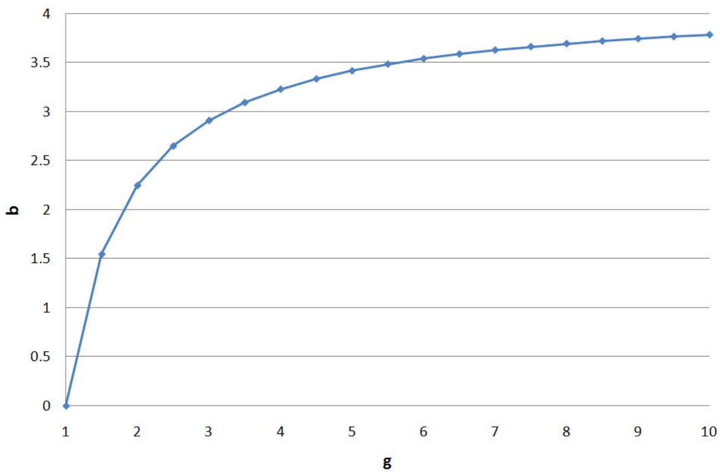


FIGURE 4.6: Node Y's ideal location with different values for g, when $e = 10$.

As e is a constant, the ideal location of Y will depend on g. Figure 4.6 shows at which distance of b the relay node Y and the peripheral node X use the same energy per period, when X is located at a fixed position $e = 10$. From the graph, it is noticeable that Y must always be closer to the CH than to X to balance the cost of transmitting twice.

4.3 Cluster communication

Inside the cluster, nodes remain listening for control messages from the CH to define their schedules. The CH can also broadcast periodic synchronisation beacons to reduce clock drift between nodes, leading to bandwidth optimisation [45]. By adding further information to the synchronisation beacon, the CH uses that same control messages to request information from the network. After the sensing and communication schedules have been established, nodes will respond to requests according to the routing algorithms implemented. Furthermore, nodes can also switch off transceiver and processing unit to save energy.

To find the best route to the CH, three different algorithms are introduced in this section, based on the theoretical findings described above: Half-Distance, Single Relay Decision and Multiple Relay Decision. Their objective is to optimise the communication inside the cluster by routing messages through other nodes, with a maximum of two hops between origin and destination.

4.3.1 Cluster formation

A new cluster formation starts from a region where N nodes are randomly deployed around the CH, a resource-rich node that manages how subscribing nodes perform their sensing and communication. All nodes are expected to be within range of at least one

CH. Considering the assumption that the distance between a relay and the origin is always at least the same as the distance between relay and CH, each cluster region is divided in two areas, as shown in figure 4.7: the area inside R region, and the area outside R. To measure distances, nodes are expected to have locationing hardware (e.g. GPS). If nodes are inside region R, they can relay information from nodes outside R. This hard limit clearly defines which nodes can and cannot route messages, simplifying decisions and reducing collisions from unnecessary and excessive relay requests. The advertisement is made periodically following each request from the CH. Nodes outside R will decide whether to communicate directly or through a relay, upon receiving advertising messages from closer nodes. An example of this displacement can be found in figure 4.7, where nodes X and Y are inside and outside R, respectively. Considering the displacement, node Y can advertise itself to node X, while X decides whether to relay messages through Y or not.

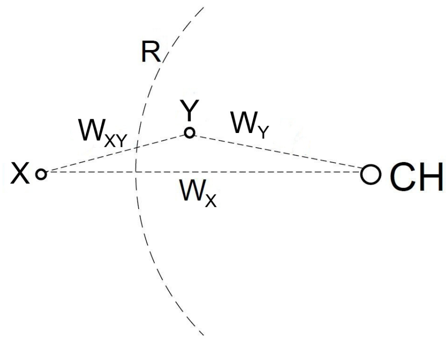


FIGURE 4.7: Displacement of nodes around CH.

The advertisement messages from potential relay nodes include a route weight information. This weight calculation is based on communication distance and energy left in the battery:

$$W_{XY} = \left(1 - \frac{E_{rem}}{E_{max}}\right) Dist^{\eta}_{XY}, \tag{4.9}$$

where W_{XY} is the advertised weight between any two nodes X and Y, E_{rem} and E_{max} are the remaining and known maximum energy values in the receiver, respectively and $Dist_{XY}$ is the estimated distance between X and Y. When the CH sends an advertisement, the receiving node calculates its distance between them, estimates its own remaining energy and calculates the direct communication weight to the CH, W_{Dir}. W_{Dir} is calculated with 4.9, where $Dist_{XY}$ becomes the distance to CH. When advertising, the node sends W_{Dir} as part of the message. Any node receiving this packet and located outside region R can estimate the weight of using the advertised route through the eq. 4.9, where $Dist_{XY}$ is the distance to the advertising node. To reduce self-interest

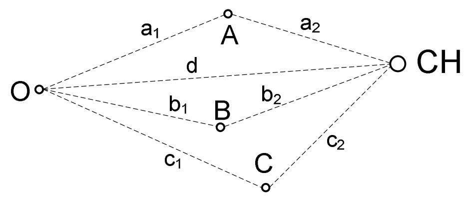


FIGURE 4.8: Example of potential routing paths.

and improve overall energy distribution, only total route weights are considered, hence the relaying weight becomes

$$W_{Rel} = W_{Adv} + W_{XY}, \tag{4.10}$$

where W_{Adv} is the W_{Dir} received from the advertising relay, and WXY is the estimated weight of using that same relay node. Equation 4.9 was derived empirically and does not represent an optimized form. It is used to show the performance of the algorithms with a method that combines energy and distance in routing decisions. Path loss exponent typically varies between 2 and 4 for outdoor and indoor environments, respectively. The remaining energy is complex to model as it depends on the chemistry of the power supply being used. A linear model can be used instead, as it is relatively close to the operating behaviour of some batteries.

Considering the displacement of figure 4.7, once X receives advertisements from CH and Y, it updates direct communication weight and calculates the overall weight if transmitting through A, being W_X the direct weight and $W_{XY} + W_Y$ the two-hop weight, should it use A as relay. The routing algorithm will then select the best alternative between the available ones. When more routes are advertised, the node follows the same procedure of calculating individual weights for each route. Figure 4.8 shows an example where node O receives advertisements W_A, W_B and W_C from A, B and C, respectively. It then calculates, for each alternative, the partial route weights W_{OA}, W_{OB} and W_{OC}, and adds to the received values.

4.3.2 Half Distance Relay

The first proposed algorithm, Half Distance Relay (HDR) is based on the calculations made in section 4.2, where the best scheme to reduce energy consumption across a routing path relies on selecting the node closer to the central point between origin and destination, regardless of remaining energy levels. As it is unrealistic to expect that at least one node is exactly in the ideal position P_i between the origin and the CH, any potential candidate must be within an area with radius R_{max} from P_i. If there are more

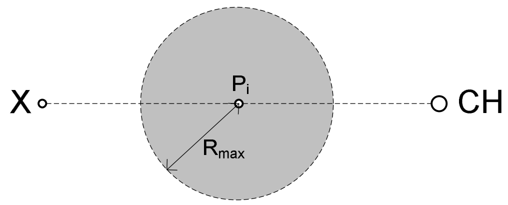


FIGURE 4.9: HDR ideal position and selection region.

than one node inside R_{max}, the origin will select the closest to P_i. Figure 4.9 shows a diagram of the position P_i between node X and CH, including the region defined by R_{max}.

4.3.3 Single Relay Decision

Single Relay Decision (SRD) uses the knowledge of total route weight to decide the best alternative between direct and each advertised options. The origin, upon receiving advertisement messages, compares them and selects the best route through

$$\text{Best weight} = Min\,(W_{Cur}\ ,\ W_{Adv}) \tag{4.11}$$

where W_{Cur} and W_{Adv} are the current and advertised route weights, respectively. This calculation is done for each received message. The path selected will be valid until one of the two following conditions occurs: (1) the CH sends a new advertisement beacon, forcing nodes to route messages directly, (or $W_{Cur} = W_{Dir}$); or (2) the relay node energy source becomes depleted, hence the origin becomes obliged to send its messages directly to the CH. When the CH sends a beacon, the receiver clears its routing table and transmits directly until a better route is found. When the relay becomes depleted, it uses the little remaining energy to advertise a shutdown process.

4.3.4 Multiple Relay Decision

Multiple Relay Decision (MRD) protocol is similar to SRD. The main difference is the use of multiple routes for each message to compensate the probability of failure of a single relay in protocols or scenarios where packet delivery cannot be guaranteed. MRD distributes the transmission through routes that present better weights than direct transmission to the CH. It uses the total route weight estimation to distribute messages more evenly through different routes. This distribution resembles the *El Farol Bar Problem* [159], a game theory problem where the inhabitants of a town decide whether they should go to El Farol Bar on a Thursday night. Since the bar is small, the population will only enjoy the bar if less than 60% of them go. It is not possible for everyone to use the same deterministic approach to the problem, as they would decide in the same manner. Furthermore, the whole population must decide at the same time, so there is no possibility of knowing if the bar is going to be full or not.

Following the same principle, a simple inductive reasoning method based on path weight was implemented. If a node has a low weight route, it is very likely that more nodes will select it as their relay, whereas another node with weightier path will not be selected at all at least until the next advertisement. Knowing the route weights for a message to reach the CH, a local decision is made in order to balance communication across different nodes.

Each node outside R resets its route table when receiving advertisements from CH and waits for nodes within R to advertise their route weight. After receiving the advertisements, nodes will select the best three indirect routes and add them to the routing table. To balance message load, each node chooses the next intermediate based on a proportionality rule. For example, if the weight of route a is half the one of route b, the probability of being selected is twice as high. An inherent aspect of this approach is that the load distribution between nodes can reduce the latency, particularly in nodes with lower weight. Figure 4.8 shows a network example where node O can choose between relaying messages to the CH through one of three nodes (A, B and C) and direct communication. Route weights are also shown in the figure, being $W_A = a_1 + a_2$, $W_B = b_1 + b_2$, $W_C = c_1 + c_2$ and $W_{Dir} = d$. If W_T is the sum of all weights, the inverse weight of each path C_i is

$$C_i = \frac{W_T}{W_i}, \tag{4.12}$$

where W_i represents the weight of each route. Calculating the probability of using path i will be

$$P_i = \frac{C_i}{C_T}, \tag{4.13}$$

where C_T is the sum of relative weights. For example, if $W_A = 11$, $W_B = 10$, $W_C = 18$ and $W_{Dir} = 20$ (as can be seen in figure 4.10), the probabilities of each route being selected are $P_A = 0.305$, $P_B = 0.335$, $P_C = 0.192$ and $P_{Dir} = 0.168$. This means that path B will have approximately twice the probability of being selected than P_{Dir}.

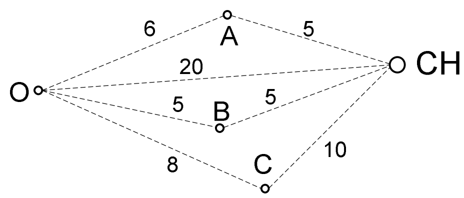


FIGURE 4.10: Example of weights in different paths.

4.4 Simulation

By routing more traffic through lighter routes, nodes are expected to achieve best overall energy distribution whilst saving energy. To demonstrate this, a simulator was developed where 50 and 100 stationary nodes are randomly deployed around the CH. Using fewer nodes than what was previously described as the potential cluster size reduces the relaying options, yet it provides an understanding of the worst-case scenario where fewer nodes are closer to the ideal location. For this simulation, the following assumptions were used:

- All nodes are within communication range of one CH.
- All nodes start with the same energy level and the transmission power is variable.
- A long-range transmitter is used, with maximum $P_{Tx} = 5.P_{Rx}$.
- All nodes are capable of adjusting their transmission power and $P_{Tx} \propto d^{\eta}$, with $\eta = 2$
- The simulation clock is discrete, and each task takes one simulation beat (simBeat) to be completed. The simBeat can be compared to a complete period in a scheduler.

In order to compare the results achieved with the proposed algorithms, single-hop (SH) and greedy (GR, based on GPSR [158]) strategies are also implemented. In GPRS the transmitter selects, between all the nodes in the network, the one that is at the same time the closest to the transmitter and in a closer range to the CH. During the simulations, the node displacement is kept for the five different routing algorithms simulated. The parameters and values used are as displayed in table 4.4.

Each node operates as a completely independent entity. CHs and sensing nodes have different tasks assigned, hence the types of messages they send are also different. The list of messages required for the simulation is described in table 4.4. Nodes generate and send one message for each CH request. The CH has two types of messages: ADV_CH and CH_QUERY. ADV_CH is an advertisement message with CH identification that

Table 4.1: Simulation parameters.

Parameter	Value
Number of nodes in a cluster	50, 100
Initial energy	200 J
Maximum T_x Energy	40 mJ
R_x Energy	8 mJ
Max. node distance to CH	1 km
Path loss exponent η	2
Advertisement range (R)	0.6 km
New message generation frequency	Every 10 sim beats
Number of runs	20

works as a network set-up message. It allows nodes to decide whether to use this CH as a sink or maintain the current one, should they be different. Furthermore, when a node receives an advertisement from the current CH, and if its distance to the CH is smaller than R (as the example of figure 4.7), it will advertise itself to other nodes. CH_QUERY message requests that all assigned nodes, upon receiving it, reply back to the CH with sensed values and within a time limit (also included in the message). A flowchart with the decision process in nodes is displayed in figure 4.11.

Table 4.2: Messages used by cluster head and nodes during the simulation.

Node type	Message type	Description
CH	ADV_CH	CH advertisement message
	CH_QUERY	CH request for sensed data from nodes connected to it
Node	ADV_NODE	Node advertisement to other nodes
	TO_CH	Message with data from the node to the CH
	ADV_SHUTDOWN	Broadcast message sent by a node with depleted power supply

Nodes, upon receiving an ADV_CH message, will verify if they are within R range. If so, they will broadcast an ADV_NODE message. In the case of SRD and MRD this message also includes the route weight value W_{Dir}. Nodes outside R listen to the ADV_NODE messages and store the best alternative in their routing tables. The value of R chosen is 60% of the maximum communication distance. To send data back to the CH, nodes transmit a TO_CH message, indicating the intermediate destination (if any). The last message type implemented is ADV_SHUTDOWN. In multi-hop algorithms the purpose of this message is to inform the network about transmitter's depletion and shutdown process, so that other nodes using it search for alternative routes.

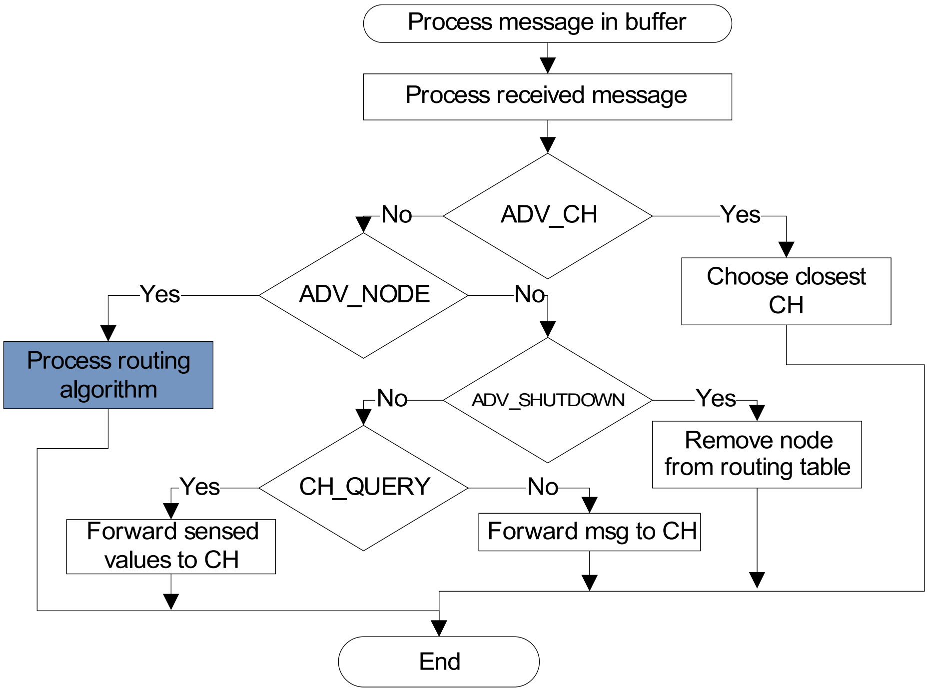


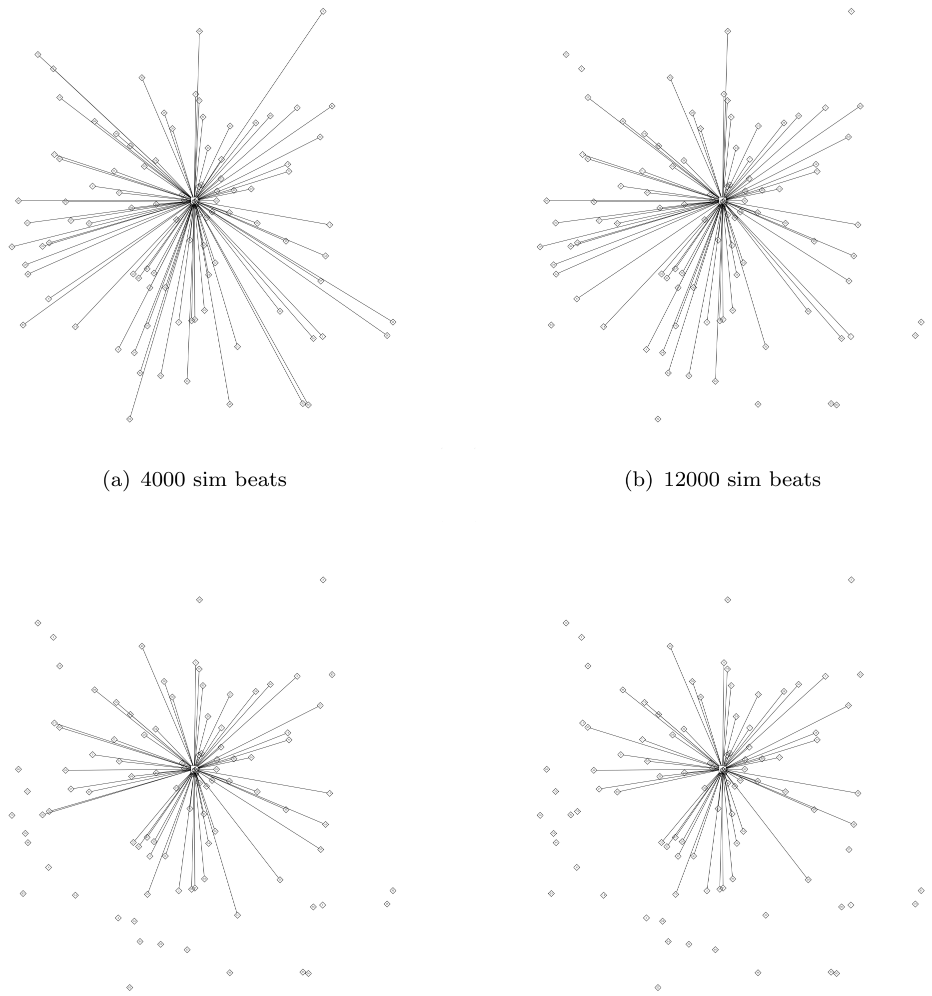
FIGURE 4.11: Routing decision flowchart.

4.5 Simulation results

Simulations were conducted using the three algorithms presented and described in section 4.3, as well as single-hop and Greedy algorithms. The results obtained from simulating these options are presented, and their performance evaluated in terms of energy usage, mean distance to CH and the sum of buffered messages. The simulation ran 20 times, with different network displacements between runs.

4.5.1 Algorithm evolution

Figures 4.12, to 4.16 show a representation of the five algorithms implemented, single-hop and greedy, with 100 nodes randomly deployed around the CH. At early stages, the network is fully connected, with multi-hop algorithms finding the best intermediates. As the simulation progresses and nodes become depleted, there are visible differences between routing algorithms. With single-hop and as expected, peripheral nodes are the first to cease their transmissions, while with Greedy the central nodes become depleted faster. Two-hop HDR only takes into consideration the halfway distance to the CH, thus there is a faster battery depletion from nodes located in the middle range of the cluster. Both SRD and MRD displayed a more uniform node depletion, with SRD having greater number of nodes alive at later simulation stages. The three two-hop proposals provide a more uniform depletion rate between nodes, improving coverage when compared to single-hop and greedy routing.



(a) 4000 sim beats

(b) 12000 sim beats

(c) 16000 sim beats

(d) 20000 sim beats

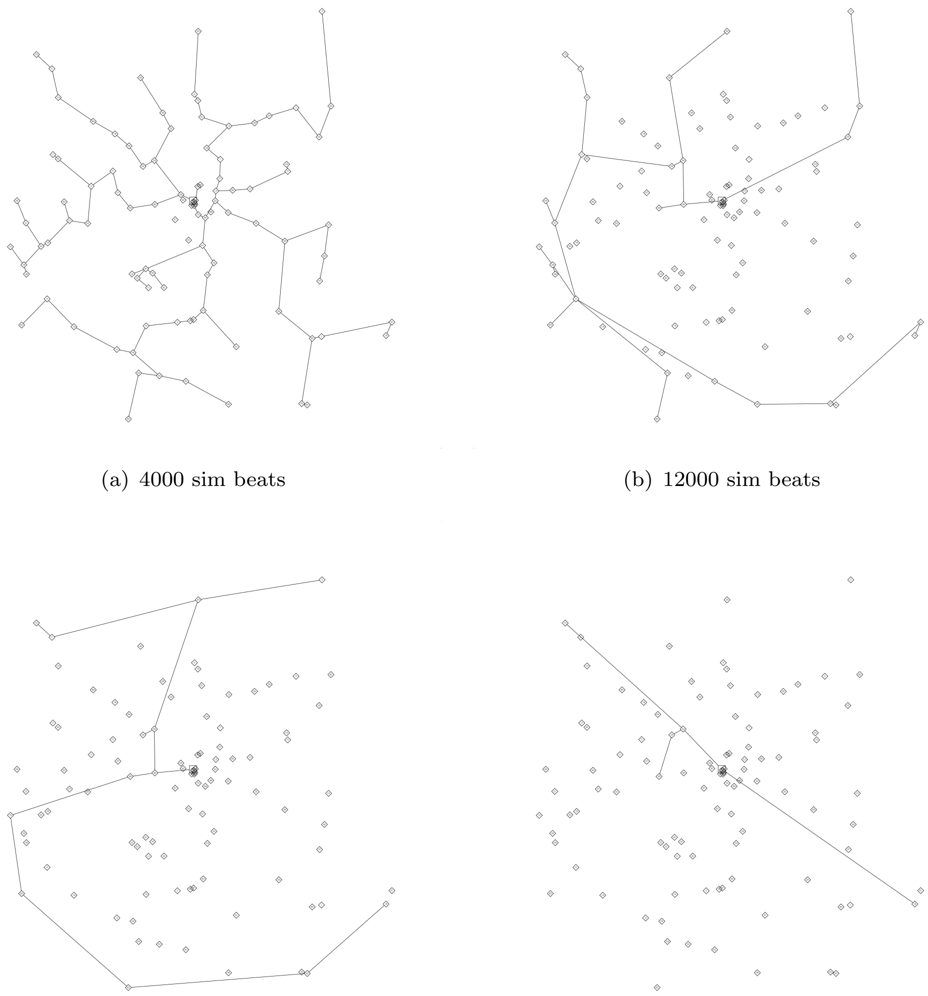
FIGURE 4.12: Example of a network evolution using a single-hop algorithm.

4.5.2 Performance evaluation

To evaluate and compare the five algorithms performance, three metrics were used:

Network lifetime. When nodes become depleted, the network loses resolution. Although a higher number of nodes than strictly necessary can be deployed, there is no guarantee that the depletion will be uniform (as seen above, depletion rate is visibly different with different algorithms). As such, keeping the nodes alive for longer guarantees a correct network operation.

Mean distance to the CH. Unbalanced depletion rates can result in different mean cluster ranges. Variations in the mean distance is an indication of the algorithm



(a) 4000 sim beats

(b) 12000 sim beats

(c) 16000 sim beats

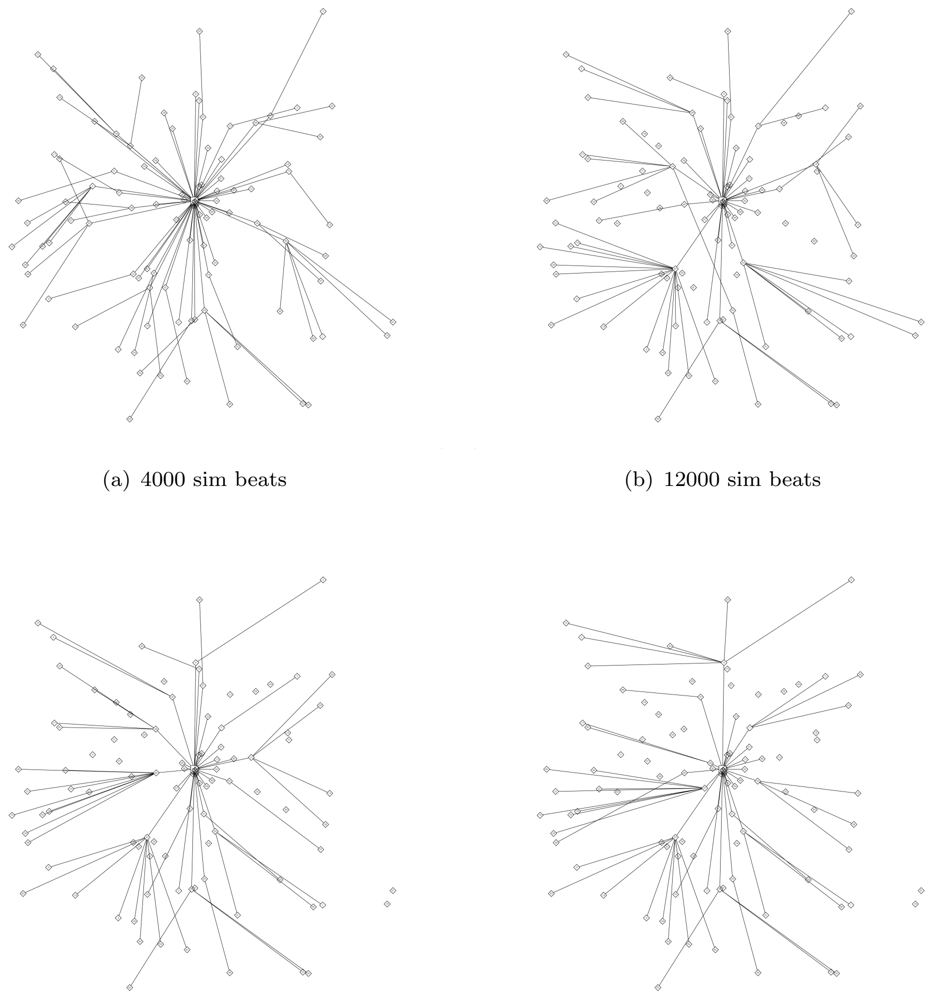
(d) 20000 sim beats

FIGURE 4.13: Example of a network evolution using a greedy algorithm.

behaviour which, combined with the number of nodes not transmitting, leads to a better understanding of whether the node loss is regional or global.

Sum of buffered messages. To avoid loss of data, nodes must transmit all buffered data before the next data acquisition and transmission cycle. This procedure is particularly important in intermediate nodes, as buffers can fill up, leading to packet losses. A balanced algorithm should be capable of keeping the node's buffers clear before the next ADV_CH.

Data aggregation strategies were not implemented. Although they can reduce network usage and consequently improve battery lifetime, they rely on nodes in a region having similar values [148]. Therefore, not using aggregation is a straightforward option that provides reliable results. Future work can consider its use and what advantages it brings.



(a) 4000 sim beats

(b) 12000 sim beats

(c) 16000 sim beats

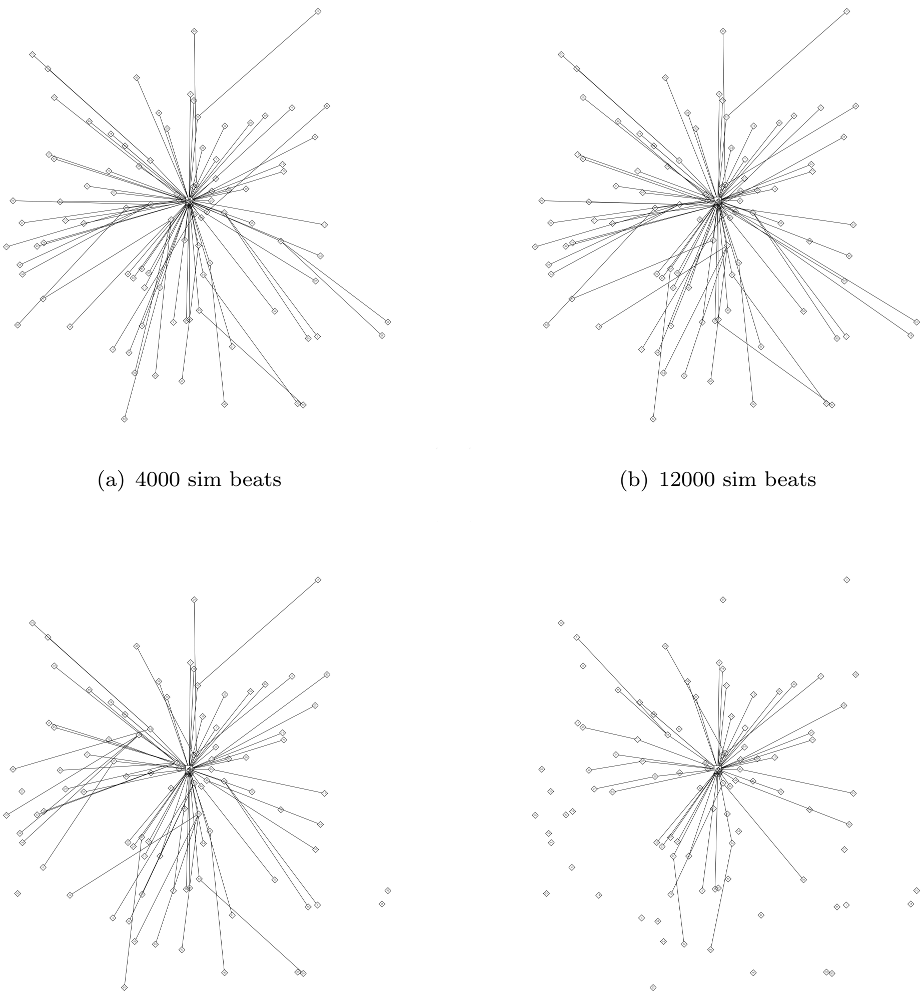
(d) 20000 sim beats

FIGURE 4.14: Example of a network evolution using the HDR algorithm.

4.5.3 Network lifetime

As previously mentioned, all nodes must be working correctly for the network to be operational. Nevertheless, due to the possibility of redundant nodes being deployed, it is assumed that the network is operational as long as 90% of them remain operating. The charts in figure 4.17 show the mean number of nodes alive throughout time for the five algorithms.

With single-hop (SH), there is a constant decrease in number of nodes alive, with similar results for different network sizes. It approaches the expected ideal depletion rate described in section 2.2.1. The node lifetime depends on communication frequency and distance to CH, since nodes operate independently from each other. With a Greedy (GR) approach, there is a decrease of network lifetime for larger networks, due to the

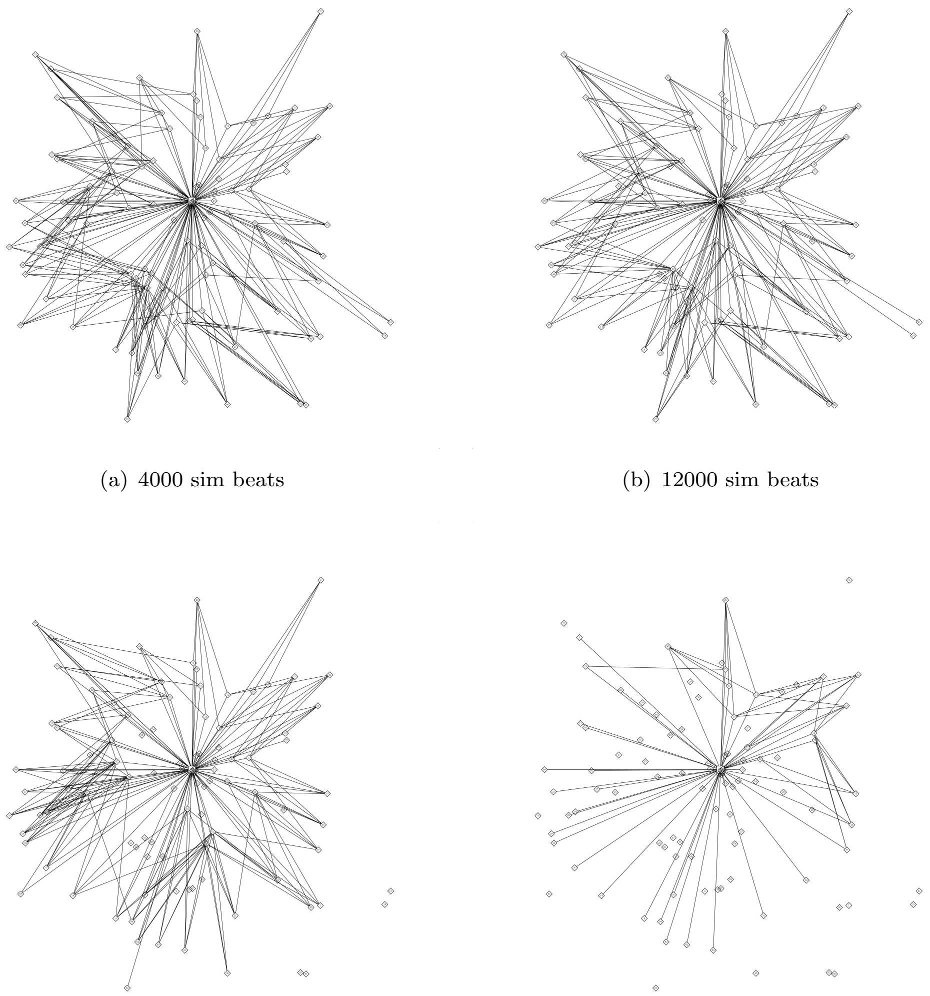


(a) 4000 sim beats (b) 12000 sim beats

(c) 16000 sim beats (d) 20000 sim beats

FIGURE 4.15: Example of a network evolution using the SRD algorithm.

additional cost of relaying more messages. As a result, less than 90% of the initial number of nodes become depleted in less than half the time of that achieved with SH. The use of HDR also resulted in a lower network lifetime than that of SH, despite its improvement with 100 nodes. Both SRD and MRD achieved longer lifetimes than SH. SRD benefits from the increase in number of nodes, leading to a 50% longer network lifetime when the cluster is composed of 100 sensing nodes (the improvement with a 50 node cluster is 43%). MRD, on the other hand, has better performance with smaller networks, yet it never reaches the same lifetime as SRD. This difference is due to the use of higher weight routes while running MRD, whereas with SRD the origin nodes keep transmitting through the lowest weight relays only.



(a) 4000 sim beats

(b) 12000 sim beats

(c) 16000 sim beats

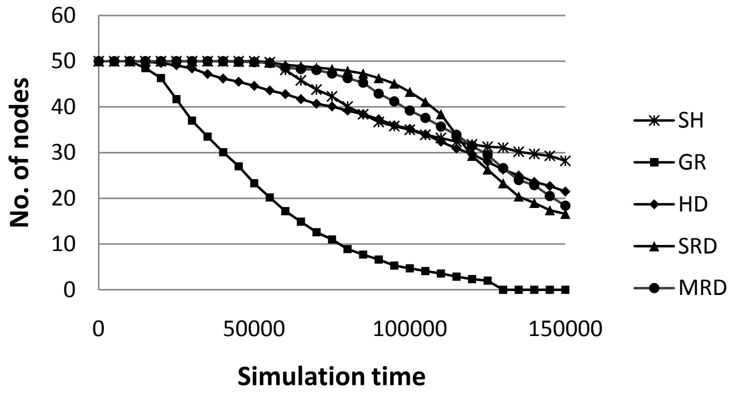
(d) 20000 sim beats

FIGURE 4.16: Example of a network evolution using the MRD algorithm.

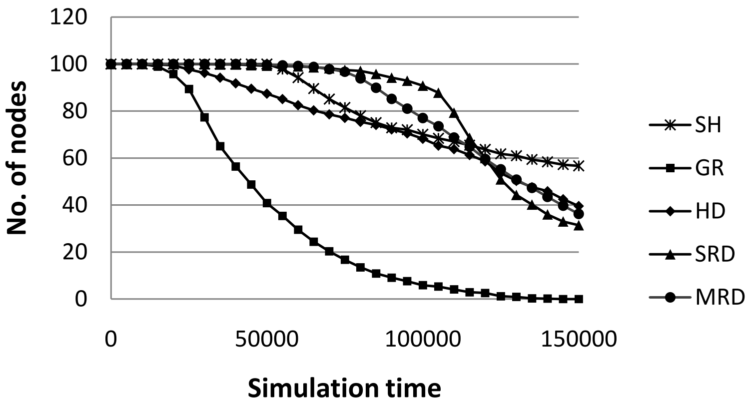
4.5.4 Mean communication distance

The knowledge of how the mean communication distance evolves is a complement to the depletion rate of nodes across the network. The direct effect of depleted node distribution during operation time is small since 90% of nodes are alive during that time. Nevertheless, the mean distance provides knowledge of how the algorithms evolve and what differences exist between them.

Figure 4.18 shows how the mean communication distance between nodes and CH evolves through time. As expected, the mean range of SH has a similar curve to that of the depletion rate. This means that nodes start dying from the periphery towards the centre of the cluster. GR shows the opposite effect of SH, with central nodes becoming depleted faster, essentially due to the additional communication of central nodes. Comparing



(a) 50 nodes



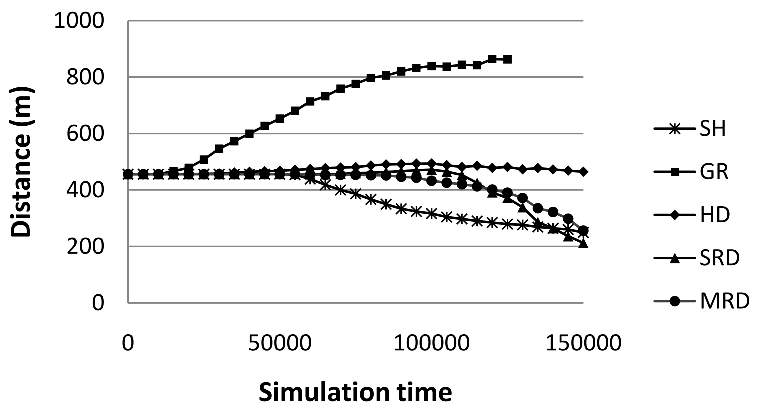
(b) 100 nodes

FIGURE 4.17: Number of nodes alive in the cluster.

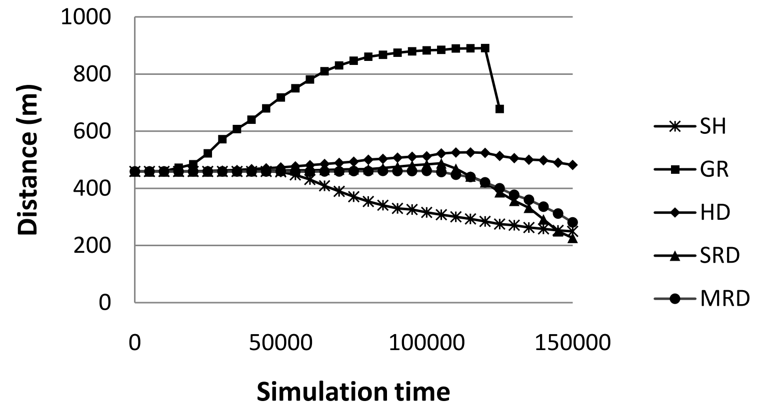
figures 4.17 and 4.18, it is visible that nodes closer to the CH are the first ones to become depleted, hence the cluster quickly loses its coverage uniformity. HDR shows a constant mean distance (the maximum difference between highest and lowest range is less than 2.6% and 15% of the maximum cluster range for the operation and complete simulation time, respectively), despite the relatively fast node depletion rate, when compared with SH. Peripheral nodes outside R are unaware of energy budget in relays. As such, they request the same node until it stops communicating. By combining distance and energy, both SRD and MRD achieve better load sharing across the cluster than HDR or GR, hence the flat mean range during the operation time (the SRD mean range difference during operation is always less than 4%, whereas the MRD difference is less than 2.5%).

4.5.5 Sum of queued messages

Another important aspect of routing protocols is latency. Using multi-hop schemes to route messages between origin and CH causes delays due to successive transmissions, retries, queuing, processing and prioritisation. Higher number of nodes also leads to a



(a) 50 nodes

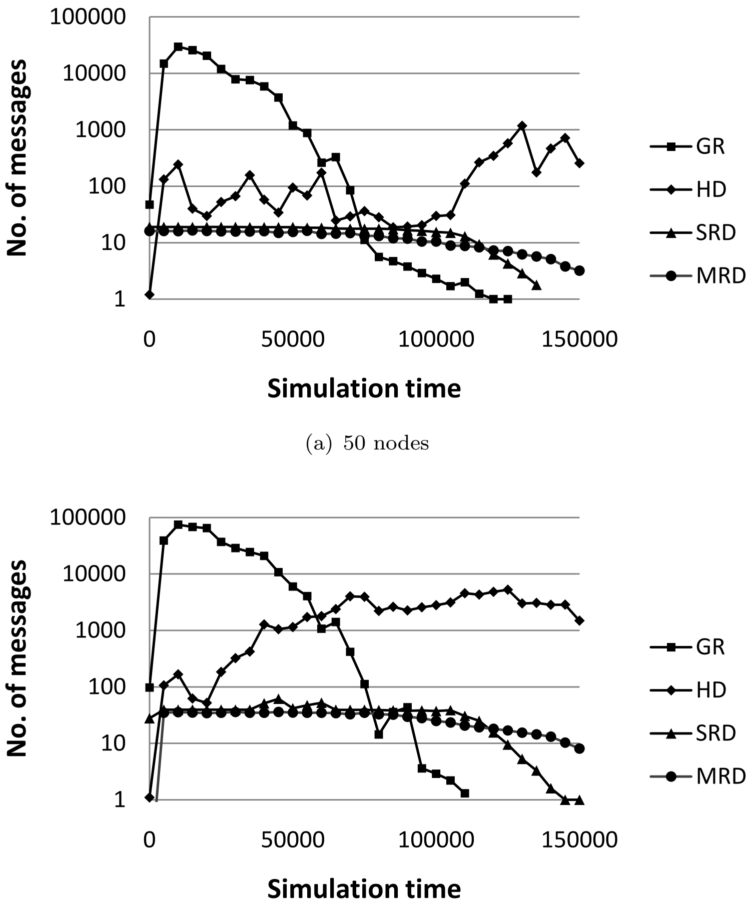


(b) 100 nodes

FIGURE 4.18: Mean communication distance in a cluster.

higher hop count between origin and destination, thus increasing latency. There are two indirect outcomes of latency: (1) the number of queued messages in a node increases, therefore the buffer will eventually overflow, leading to message loss; and (2) the relaying process is not uniform across the cluster, leading to uneven relaying between nodes and faster energy depletion. For these reasons, having a routing algorithm that balances message relaying across the cluster leads to improved delivery through lower latency and message loss.

In the simulation, latency is measured from the moment the origin prepares a new message until the moment the CH receives it correctly (lost messages are not accounted). Figure 4.19 shows the sum of queued messages in all nodes across a cluster. A new message is generated by each node every 10 simulation cycles, leaving the remaining time to handle and forward received data. SH was not included since it has no queued messages at Routing level. GR, as an extreme case of multi-hop routing, shows a constant and exponential increase in queued messages, where the curve drops are due to nodes becoming depleted. To achieve a stable number of queued messages, the number of simulation cycles between new message generation has to be larger than 10. Nevertheless, this number must increase proportionally with the number of nodes in the cluster, as visible by the difference between the 50 and 100 cluster nodes' charts.



(a) 50 nodes

(b) 100 nodes

FIGURE 4.19: Number of messages accumulated across the network.

While balancing communication weight, SRD and MRD also distribute the messages more evenly across the network. As such, the number of buffered messages is very low and it never reaches 100 messages accumulated throughout the cluster. The main difference between SRD and MRD (visible during the simulation runs) was that SRD accumulates a higher number of messages in few, well-located relays. Message queuing was low with MRD routing, as its load sharing was the most uniform among the 5 alternatives.

4.6 Discussion

This chapter evaluates single-hop and two-hop routing and its effect on energy usage in a cluster. It was shown that if nodes can communicate directly with the CH, relaying a message with two-hop routing only allows energy savings if $P_{Tx} > 2.P_{Rx}$ and the relay node is within a specific area between origin and the CH. Moreover, and depending on relay node location, two-hop can also improve energy usage distribution across the network when compared with single-hop.

Topology management with two-hop routing requires a degree of complexity superior to that of single-hop. Although the relaying process and decision has a set of rules that needs to be detailed and optimised to provide better results, the hardware and software requirements are minimal: three different types of messages and two-entry routing tables (or four for MRD). This accounts in an increase in communication overhead, compensated by the overall energy saving and load sharing.

HDR provides an insight of how a pure distance-based approach behaves in a cluster-wide scale, helping to further understand the complexity at scale of the two-hop routing strategies. The HDR algorithm showed a worse mean lifetime than single-hop during the useful network operation. The route selection overloaded intermediate nodes, which led to their early energy depletion. Nevertheless, the biggest drawback of HDR is the high latency, due to the number of messages buffered in intermediate nodes, further aggravated by premature depletion and resulting in increased delay and buffer overrun. As such, it becomes clear that although a single peripheral node aims at sharing energy consumption between origin and relay to prolong network lifetime, this procedure can result in a greedy usage of the relay resources when considering a cluster-wide point of view. If only one origin selects a certain relay node due to its ideal position, the energy usage and battery depletion is as expected. Yet, when more than one origin choose the same relay, its depletion rate accelerates. Considering the cluster-wide perspective, once a relay node becomes depleted, the origins using it will search for alternatives. These origin nodes eventually end up selecting intermediates which are already re-transmitting messages from other sources, further accelerating their energy usage.

The two weight-based strategies were developed to minimise the effect of multiple origins per relay node. The use of static network displacement increases the importance of understanding and integrating a process that balances communication between nodes according to the remaining energy. Of the two weight-based proposals, SRD achieves a longer lifetime than any other algorithm (over 50% longer than single-hop). However, it did not distribute the load as evenly as MRD, which avoided the bottleneck effect in relay nodes. Considering network lifetime alone, SRD is the best alternative. However, if near-real-time message delivery is combined with improvements in lifetime and latency, MRD diplays better results. Both MRD and SRD proved to be more efficient than Greedy, while having better coverage and energy distribution than single-hop. SRD showed an overall node depletion rate that approaches the ideal case where all nodes die at the same time.

There are no significant differences between a cluster that is formed of 50 or 100 nodes while using single-hop routing, as there is no interaction between sensing nodes. On the other hand, all multi-hop algorithms are affected in different ways:

- Greedy algorithm affects both lifetime and message buffering. When the number of nodes doubles, the lifetime is reduced (although not significantly) and the number of messages accumulated in buffers increases to more than double.
- The use of HDR has little effect on the lifetime (less than 5% difference between 50 and 100 nodes), as the decision of forwarding messages based solely on distance is highly inflexible. Nevertheless, there is an increase in buffered messages when the number of nodes doubles.
- SRD shows improvements in energy distribution and lifetime (approximately 5%) when the network size increases, therefore it benefits from having a larger number of nodes. Moreover, the latency is not severely affected by any of the cases, although there are nodes that at times can accumulate more messages than they can transmit.
- MRD's lifetime was reduced by approximately 5% with the increase in number of nodes. Although it shows a longer lifetime than single-hop, it never reaches the lifetime of SRD, mainly due to the use of higher energy routes. Nevertheless, the latency is always low across the network and there are no bottlenecks.

There are trade-offs between the algorithms presented. While single-hop is a simple and straightforward algorithm that shows little delay in message delivery and a predictable network lifetime, its use relies on nodes being constantly within communication distance of a CH. Greedy uses the closest route to send messages, resulting in higher energy usage and latency. Nevertheless, it can prove to be solid strategy in smaller networks where only a limited number of nodes is within direct reach of a CH. The two-hop strategies are a balance between both: they balance energy usage with latency and, if necessary they can be adapted to extend the cluster range.

4.7 Summary

Energy usage is one of the basic metrics in WSN development. It is an underlying reason of limitations in nodes' hardware and software. Understanding and minimising energy usage is therefore part of the challenge in the development and adaption of routing algorithms for sensor networks.

The comparison between single-hop and multi-hop techniques gives an insight on how the energy is used by not only one node, but also by a cluster and the whole network while working cooperatively. It becomes clear that nodes must rely on each other and work cooperatively for a cluster to extend its operating time.

Two-hop schemes are the simplest of multi-hop schemes. In this chapter it was shown that they guarantee extended lifetime when compared to single-hop, as well as better energy distribution, at the cost of a predictable increase in latency. There are different approaches to two-hop routing algorithms, and the ones presented proved that even simple decisions can affect the final performance significantly. Furthermore, it was shown that, to achieve the best results, nodes must be aware of not only their status, but also of the status of possible relays. This way, it is possible to reduce self-interest and improve overall cooperation. The results showed that a combination between energy and distance result in a metric that improves the network lifetime, approaching the ideal solution where all nodes become depleted simultaneously.

Chapter 5

WSN simulation and environment-aware communication

Simulation environments provide a first and quick way of testing new solutions before implementation, reducing development cost and time. In this chapter, a new simulator is presented. Its objective is to provide a framework to test and optimise communication strategies between nodes deployed at sea, based on the realistic environment models. In addition, a new environment-aware adaptive engine is presented and its operation described. The engine uses data gathered from both the environment and network status to adjust node's behaviour and improve performance.

5.1 Sensor network simulation

To fully understand the network behaviour and performance, the WSN must be deployed in its operating environment. By doing this, all the foreseen obstacles and challenges addressed during the development stage — as well as any unexpected issues or details — can be correctly assessed so nodes are modified accordingly. In the particular case of WSNs at sea, the deployment would help understanding how weather changes influence the network performance. However, this is an unfeasible option for the length of this research. Nodes would have to be designed to comply with regulations of maritime organisations, and the deployment would have to be done using boats, aeroplanes or helicopters. Furthermore, it would be necessary to test the network under different weather conditions, from clear sky and flat sea, to strong winds and rough sea. Other solutions, such as small scale deployment or setting up a network in alternative environments (i.e. tanks, lakes or rivers) may provide a different feedback to that of large-scale maritime deployment and consequently induce in detail errors.

The alternative to a complete deployment is to study the weather and how it interferes with communications between nodes through simulation. It allows quick changes and adjustments in the configuration to simulate different scenarios and achieve the best performance trade-off under the expected deployment conditions.

Understanding how the weather influences the route set-up and communication between nodes is fundamental for the simulation development and consequent results and decisions. As described in section 2.5, there are different off-the-shelf simulators for WSNs, each one with advantages and drawbacks. In any case, no simulator provides the complete framework as it is required for this work. There are two options for the simulation development: (1) re-do a significant part of one of the existing simulators or (2) to design a new simulator based on the most realistic models and assumptions found in literature. This work is based on the second option, due to the flexibility of designing and integrating the components from start. Moreover, it is faster and more reliable to tune a specifically developed simulator once results are obtained from a real deployment, as all the code is know and specifically tailored.

In this section, the cross-layer WSN simulator development is described. The communication between nodes is of particular importance, since the level of detail of both environment and channel models are essential to provide realistic results. The Medium Access Control and Routing layers are based on the models described in chapters 3 and 4, which are adapted to fit the full simulation structure and requirements.

5.1.1 Challenges

The main aim of this thesis is to create a sensor network that operates under variable environmental conditions. To this extent, the accuracy of simulation models is influential to the development of new algorithms and protocols. Their correctness will influence the design decisions. As previously highlighted by Raman and Chebrolu [39], the best way to develop a WSN is by understanding its deployment scenario. Only a complete development that includes thorough understanding of the application, hardware selection and software development can provide the best compromise for the targeted application. To that extent, two areas will be addressed and cross-examined: deep understanding of the case scenario and the development of networking algorithms according to the findings and assumptions described before.

5.1.2 Assumptions and definitions

The simulation focus on the communication aspect of the network. Nevertheless, assumptions are needed to address all other aspects inherent to WSNs. To provide a more accurate description of node's characteristics, the assumptions must reflect a realist point of view:

- The positions of the nodes are random and the nodes are static during the course of the simulation. Although a real deployment can show a relative movement between nodes, it is expected to be slow and predictable, hence it is not sudden change on network topology is expected.
- A single network can theoretically extend to several thousands of nodes. Using a clustering algorithm provides independence between nodes, where only the CHs manage subscribing nodes. In real deployments there are some interferences between clusters, are expected to affect frontier nodes. Nevertheless, in the simulation it is assumed that each cluster can work with no interference from adjacent clusters.
- Sensing and locationing mechanisms are assumed to be present, and the data acquired by these is promptly available to the application layer. The simulation will be confined to networking issues only.
- Clock drift is not considered. Although in some practical cases this drift can be large enough to affect synchronism between nodes, it is not expected to be large enough to affect node's operation during simulation.
- The path loss exponent is kept constant throughout each simulation run.
- There is no interference or attenuation from rainfall. As recommended by the International Telecommunication Union [160], the rain only affects communication beyond 10 GHz. Nevertheless, this can be
- The transceiver switching time between Rx and Tx operations is instantaneous. As such, there is no collision caused by transmissions that start during transceiver's transitions.
- When a route between two nodes is established, it is valid for at least the duration of the communication process. However, there is a time limit applied to back-offs.

5.2 Modelling wireless communication

The communication model is an essential part of a simulation: depending on its detail, it can provide a correct understanding of how the packets are sent across the network. In this thesis, a realistic scenario is the basis of the research, thus the simulation. The model used must reflect what can happen when nodes are deployed at sea. In the proposed simulation, the aim is to understand how nodes interact with each other — how hidden and exposed terminal problems occur, and what are the rates of packet collision and loss — for a given set of network and weather conditions. These conditions demand a realistic model where nodes suffer the effects of being deployed with a variable number of neighbours and unpredictable conditions.

In a network every node is a potential receiver, as long as the received signal is strong enough to be decoded correctly. This calculation is done at bit level: when decoding the signal, a node estimates the Bit Error Rate (BER) probability and, if below a pre-defined sensitivity, it discards the message as being too prone to have errors. The complete transmission, reception and error estimation process is shown in figure 5.1.

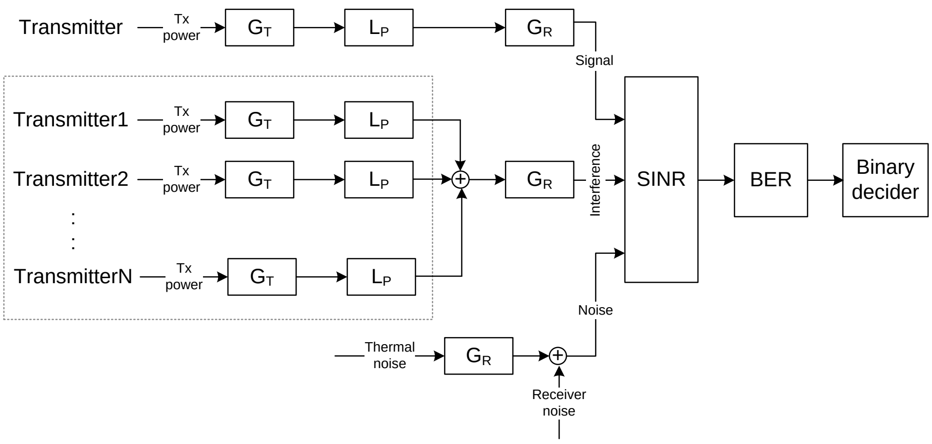


FIGURE 5.1: Communication diagram for correct transmission decision.

Common models are divided into Fading and Path Loss. Fading represents the signal distortion over the propagation media [69]. Obstacles, for example, can cause the loss of the line of sight between sender and receiver, giving shadowing or slow fading. Fast fading, on the other hand, results from interferences caused by moving objects that reflect the signal frequencies. Frequencies above 1 GHz are particularly sensitive to this aspect. Flat fading results in all components of the signal to react in the same manner. Fading can be frequency selective.

Path loss represents the attenuation of a signal travelling through space. It is affected by everything between transmitter and receiver, such as terrain contour, air moisture, vegetation, distance between sender and receiver, and the height and location of antennas. Multipath of the signal can either increase or decrease the received signal strength. Rayleigh fading assumes that the amplitude of a signal passing through a medium varies randomly. This is specific to cases where there is no line of sight. When there is a line of sight, Rician fading is more adequate, as it models the line of sight along with the reflected signals. Along with path loss and fading, there is still noise due to transmission or circuitry to consider.

The received power is determined by equation 5.1, where $P_T\,[dBm]$ is the transmitting power, $P_R\,[dBm]$ is the receiving power respectively, $G_T\,[dBi]$ is the transmitter antenna gain, and $G_R\,[dBi]$ is the receiver antenna gain. All these factors are known beforehand. $L_P\,[dB]$ is the path loss. Equation 5.2 shows the calculation of path loss, where η is the path loss exponent and X_σ the gaussian zero-mean random variable (RV) with standard deviation σ (equation 5.3). This is an adapted model from Zuniga and Krishnamachari [161], Seada et al. [162], and the IEEE 802.15.4 standard [61], which in its turn is an approximation of the log-normal shadowing channel model, also used in the Castalia simulator [126]. The use of the Gaussian zero-mean RV to the 802.15.4 model introduces a randomness that is meant to reproduce transmission irregularities.

$$P_R\,[dBm] = P_T + G_T - L_P + G_R \tag{5.1}$$

$$L_P\,[dBm] = \begin{cases} 40.2 + 20log_{10}d + X_\sigma & ,d \leq 8 \\ 58.5 + 10\eta log_{10}d + X_\sigma & ,d \leq 8 \end{cases} \tag{5.2}$$

$$X_\sigma \sim N(0,\sigma), \quad \text{where } 2.8 \leq \sigma \leq 6.4 \tag{5.3}$$

The transmission is affected by waves, as mentioned in chapter 1. If a drifting node tries to communicate, it will do so immediately (on flat or nearly flat conditions) or when it reaches the crest (if waves are higher than the antenna). The receiver must also be close to the crest to receive the message. Assuming that the transmitting node can detect when it is close to the crest, the probability of another node receiving the packet is calculated using equation 5.4, where h is the antenna height (above water level) and H is the wave height. Alomainy et al. [163] evaluated antenna performance of 2.4 GHz transmissions in a wireless Body Area Network. The measurements were done at chest level, and showed an attenuation of $\approx 60-70$ dB. Considering that the human body is mainly water and the chest depth is $\approx 25-30$ cm, the attenuation can be as high as 280 dB/m. As such, and to simplify the wave interference calculations, it is considered that if a wave blocks the line of sight between sender and receiver, the attenuation will cause the transmission to be completely lost.

$$p_{Rx} = \frac{h}{H} \tag{5.4}$$

On the receiver side, if there is no interference from any other source, the received signal is only affected by noise. The Signal-to-Noise Ratio (SNR) will be calculated using equation 5.5 [68], where N_0 is the noise power. If, on the other hand, N nodes are transmitting at the same time, then equation 5.6 will be used, where I_i is the interference power of a given node i. N_0 is calculated using equation 5.7, where k is the Boltzmann constant ($1.381 \times 10^{-23} J/K$), τ is the temperature, and B is the bandwidth.

$$SNR\,[dB] = 10log_{10}\frac{P_{Rx}}{N_0} \tag{5.5}$$

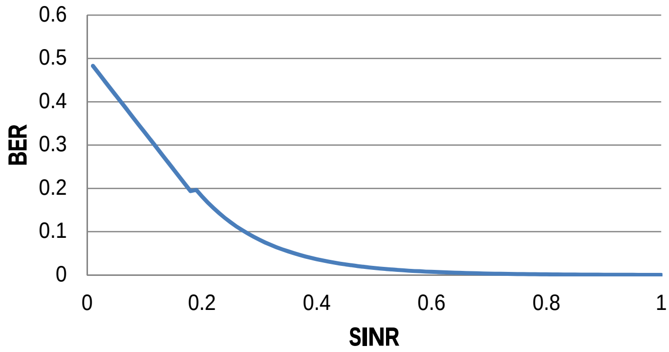


FIGURE 5.2: Geometric representation of BER according to changes in SINR.

$$SINR\,[dB] = 10log_{10}\frac{P_{Rx}}{N_0 + \sum_{i=1}^{N} I_i} \tag{5.6}$$

$$N_0 = k\tau BG_R \tag{5.7}$$

The BER is calculated with respect to the SINR, by using equation 5.8 [164]. This is an approximation to the 802.15.4 model for BER. This simplification is used due to the complexity of the original calculation.

$$BER = \begin{cases} -1.7SINR + 0.5 & ,SINR < 0.19 \\ 0.9e^{-8SINR} & ,SINR \geq 0.19 \end{cases} \tag{5.8}$$

The BER works as a binary decider: if it is above a pre-defined value (typically 10^{-5}), then the message is considered as not having any error; otherwise, the probability of error is high and the message discarded. Although the BER limit is fixed, the log-normal shadowing channel model with Gaussian zero-mean RV already introduces the randomness necessary to make this estimation realistic. The graph in figure 5.2 shows the outcome of BER calculation as in equation 5.8.

5.3 Simulator architecture

The simulation is based on a modular approach, where every module represents a different component of the network: nodes, CH and communication channel. In addition, other modules are required to support the simulation environment: a Real-Time Clock (RTC) and packet handler. A simplified diagram showing these modules and how they interact is shown in figure 5.3.

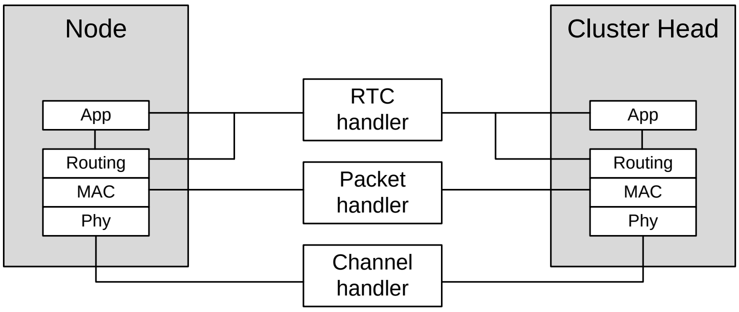


FIGURE 5.3: Simulation modules and their interaction.

5.3.1 Nodes and CH tables and status

In a cluster network, the nodes and CH have different purposes and operation. In the particular case of this work, the CH is also physically different from the sensing nodes. As such, the CH is a different module that shares the underlying network stack layers (PHY and MAC), but has differences in Routing and Application layers.

Each node decides its schedule autonomously. To keep a global track of time, the RTC is used to identify the absolute simulation time and alarms, triggering the start of new events to each node individually. It is then up to nodes to decide its following task and status individually, stored using a triplet $< time, node, nextStatus >$, where $time$ is the absolute starting time of an event, $node$ is where that event will be directed to, and $nextStatus$ identifies the type of event, whether reply, transmission, or relay.

The unpredictable network size and weather conditions make reactive algorithms and on-demand route establishment more attractive. Each route is only valid for one transmission, as waves can randomly appear and block the path. The nodes and CH have specific types of packets that they can transmit, as listed in table 5.1. This procedure also eliminates the need for routing tables. The cost is an increased overhead and latency to establish a new route when a new transmission is required. Proactive routing, on the other hand, would have required constant updates from nodes, discovering new relays and maintaining a reliable routing table, which would have also led to increased overhead, hence energy usage and collisions, although latency directly related to route establishment is reduced.

The diagram of figure 5.4 shows the sequence steps of a successful transmission. Each transmission starts with the CH broadcasting an ADV_CH message, advertising its status and transmission time window t_{adv}. Nodes select a random transmission time t_{tx} between current time t_{curr} and $t_{curr} + t_{adv}$ to transmit their data. Once t_{tx} arrives, the transmitting node broadcasts a REQ_ROUTE packet to search for a suitable relay. The receiving nodes will then follow a delayed reply strategy, where the delay time t_{reply} is calculated according to the routing algorithm in use. Once t_{reply} delay has timed

Packet type	Description
ADV_CH	CH advertisement (exclusive to CH)
REQ_ROUTE	Route request from a node wishing to send data
ADV_NODE	Reply from CH or any potential relay node to a route request
TX	Data packet

TABLE 5.1: Packet types used in the simulation.

out, the node transmits an ADV_NODE packet back to the origin node, so that the origin decides (based on the routing algorithm) if to transmit through that node. This procedure is different from that used in chapter 4. This change is due to the need of confirming the route just before transmitting, in case of harsh weather and waves blocking the line of sight between nodes. The maximum duration of an established route (before re-calculating if a new obstruction occurred) is 1 second.

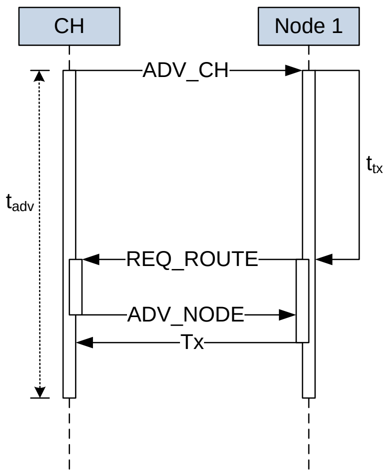


FIGURE 5.4: Transmission sequence diagram.

Internally, the nodes and CH have a network stack divided into four layers: Application, Routing, MAC and PHY, as shown in figure 5.5. The application layer is responsible for the interaction between sensing, energy and communication. The routing layer decides when and how nodes transmit the sensed data, as well as messages received from neighbours. This layer is different for nodes and CH.

Each node must individually decide whether and where to relay their messages, with relay nodes making no differentiation between self-generated or received ones. The new message generation starts in the application layer, while relaying process starts when receiving a new data packet (physical layer) and entails decisions that involve processes at MAC and Routing levels. Figure 5.6 illustrates the relaying of one message generated in node A, which is subsequently relayed by node B and finally received by the CH.

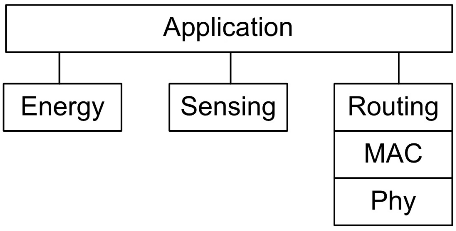


FIGURE 5.5: Node communication stack.

Each layer has different methods to forward messages to the adjacent layers, as shown in figure 5.7. Due to the specific tasks of each layer, messages are led to follow the structure orderly.

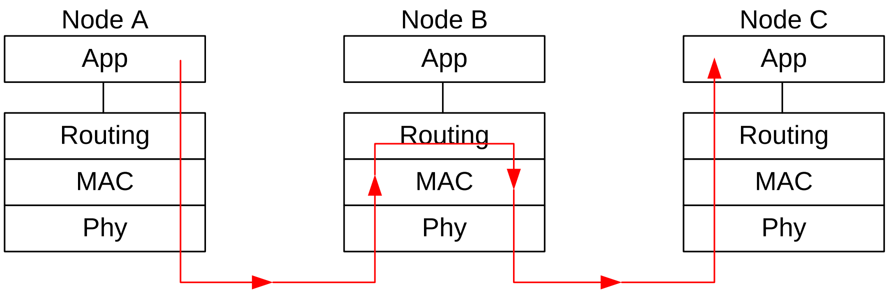


FIGURE 5.6: Message relaying process.

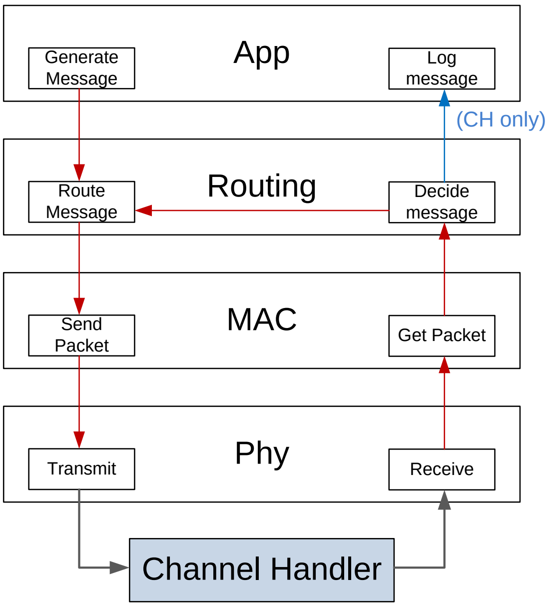


FIGURE 5.7: Message creation and routing decision sequence in nodes.

The sensing and communication processes start in the application layer. It manages node's schedule, data acquisition and aggregation, monitors energy usage, and decides which data will be transmitted. In the simulation, only energy and communication modules were implemented. CH and nodes have different implementations: nodes must be aware of energy usage, sensing and data generation timings, whereas the CH is not expected to have these limitations; instead, it will gather all data from the network, process and store it at least until an eventual transmission out of the cluster.

5.3.2 Energy

The energy usage and management is a fundamental issue in any WSN development. In the particular case of a localised deployment at sea the network is not expected to run for more than four weeks in normal conditions. However, it is still important to make sure that the power supply lasts long enough to guarantee a stable network operation and recovery procedure.

Considering the energy distribution mentioned in section 2.2.1 and the fact that wireless transmission is the prevailing factor for battery depletion, only energy consumption from the communication hardware is considered. The values can be based on those found in datasheets or measured through deployments. As nodes may not need to transmit at full power every time, an approximation with the inverse square law is used for shorter transmission ranges.

5.3.3 Simulation clock and runtime

The simulation uses a discrete, pseudo-RTC, where events are executed sequentially once the clock reaches its starting time. To simulate collisions, contention and other network issues, events are concurrent. If two or more transmissions occur simultaneously or one starts while the other is ongoing (e.g. hidden terminal problem), the interaction and overlapping between both is measured and each node affected will decide individually which action to take.

The RTC does not interfere with operations performed by nodes. The information about node's next status and operations is stored and decided internally through the triplet $< time, node, nextStatus >$ in each node's task queue. Its function is solely to trigger an alarm in each node so that they start the event handler.

5.3.4 Packet and channel handling

Whenever the CH or any other node decide to transmit, they must generate a new packet. For resource-saving purposes, all packets are store in a common packet handler. Each packet has a unique identifying pair $< packetID, packet >$ for correct access and manipulation. Once the new packet is stored in the packet handler, the node will signal its transmission to the channel handler. For each transmission, the channel handler identifies relative network locations and nodes within range of the transmitter through the equations described in section 5.2. Because of the number of nodes and coverage region size, each link is calculated independently. All nodes within range and with no interference from waves receive, along with the message, the calculated receiving power figure, so that they can estimate interference and BER.

Although it is possible that weather conditions and interferences across the monitored region change significantly, there are known limits to maximum and minimum values, therefore it is assumed that the combination of results using different parameters is sufficient to understand the overall network performance. For that reason, path loss and wave height are pre-defined and there is no variation throughout a run, yet they are changed between different runs.

5.4 Network algorithms

The two top layers of the network stack are responsible for the way that nodes access the communication channel and in which conditions they do so. The Routing layer decides where to send the information, whether and how to answer any incoming request. The MAC layer defines the underlying access methods, detects if the channel is free to transmit, if incoming packets were correctly received and are destined to that node, and if the hardware can be switched off to save energy. In WSNs it is beneficial to have a holistic view of network layers and algorithms, as resources are limited and cross-layer optimisation can improve network efficiency.

5.4.1 Routing

Nodes follow simple routing procedures and rules, and they are triggered by two events: new transmission and incoming packets. A new transmission occurs upon a CH request and t_{Tx} timeout. The message is then sent to the lower layers to be transmitted. When nodes receive packets, either an advertisement or data packet, they identify if it is their task to forward it to the next relay, or ultimately the CH.

Packet relaying process depends on the routing algorithm being used. The algorithm decides if the node should reply or not to the received request. The direct application of the routing protocols from chapter 4 is not feasible. When implementing the simulator, it was found that the overhead caused by all the answers from relay candidates stalled the network. The solution implemented consists of a delayed reply mechanism. The delay is calculated with equation 5.9, where d_{xy} the distance between receiver and an ideal location, and κ is a constant. The ideal location depends on the routing algorithm in use. For GPSR-based Greedy, for example, this location is *"(...) the neighbour* *geographically closest to the packet's destination"* [158]. On the other hand, for SRD and MRD, the ideal position is the closest to the geographic centre between origin and CH.

$$t_{reply} = d_{xy}\kappa \tag{5.9}$$

5.4.2 Medium Access Control

The MAC layer switches between three states: transmitting, listening and sleeping. Transmission depends on packets received from the Routing layer, while the transition between listening and sleeping states is controlled at Application level. Nevertheless, it is up to the MAC algorithm the final decision of whether it executes the instructions received from the upper layer. The MAC layer follows the principles discussed in chapter 3. It decides if it is possible for a node to transmit (i.e. no potential collision is detected) or not, and which procedure to follow. Three options were implemented: no back-off, one time back-off and multiple back-offs. The full simulation shows how large the differences between them are and what influence they bring to the overall network performance. RTS/CTS scheme was not implemented, as it is replaced by a handshaking process at Routing level.

5.4.2.1 Physical layer

The physical layer is based on the models described in section 5.2, and it is responsible for all the interactions with the channel handler. It transmits and receives packets, calculating SINR and BER. Collision estimation is an important issue to consider: how receiving nodes decide which is the strongest signal and if it is strong enough to be decoded correctly. The choice is to use the first signal that is strong enough to be decoded correctly, and all subsequent transmissions will cause collisions and packet losses. If one or more transmissions overlap while a node is receiving a packet, the interference level will be calculated based on the maximum sum of received signal level at any instant.

5.5 Opportunistic routing in blind nodes

The opportunistic use of surrounding nodes to forward messages in dense networks is an addition to networks with significant disruption in communication [165]. The simulation uses reactive routing strategies. As described, this option is more suitable for larger networks. Nevertheless, when nodes cannot receive the ADV_CH message, they have no means of transmitting their data. This decision can affect the network when operating under harsh weather. Opportunistic routing from blind nodes is a strategy aimed at minimising this effect, by allowing nodes to search for a relay with a known route towards the destination. It can also allow an extended coverage and increased message delivery by expanding the original two-hop and greedy algorithms.

Opportunistic routing consists of making blind nodes aware of any ongoing transmission towards the CH and use the sender as a relay for their data. Due to REQ_ROUTE and ADV_NODE negotiation, visible nodes only transmit data once another node advertises itself. In the case of a reply from the CH, nodes are guaranteed to transmit directly, being hidden nodes the only obstacle. Blind nodes can use any transmitting node as relay, independently of location, making the process epidemic and undirected. Figure 5.8 shows the difference between visible communication (left), where only nodes within transmission range (inside the dashed area) can send data to the CH; and with opportunistic blind nodes (right) that will transmit using any possible relay (represented by red lines) independently of range or location. In addition, the algorithm can also work recursively, where opportunistic nodes become relays for each other.

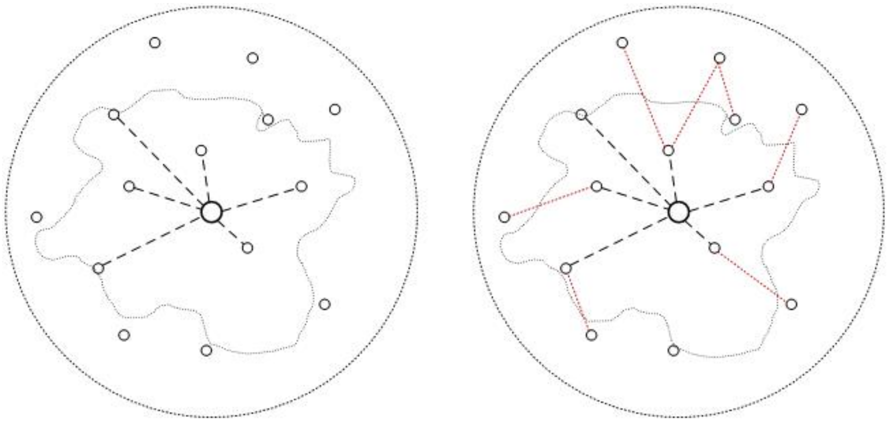


FIGURE 5.8: Diagrams where only visible nodes transmit (left) and with added communication from opportunistic blind nodes right.

Nodes that do not know which CH is within range have two options to find a suitable relay. The first consists of a proactive route discovery, where a node queries its neighbours for possible routes towards the CH. If the potential relay has a defined route to the CH it replies to the request. All other nodes use the same proactive technique to discover their own routes. The end result is a reverse tree build as shown in the diagrams of figure 5.9. The second option consists in building reactive routes when a transmission is detected. Since all routing techniques work reactively in the first place, with REQ_ROUTE and ADV_NODE messages being sent to create temporary routes, blind nodes only transmit once a TX message is sent across, to certify that the transmitting node has an established route towards the CH. Consequently, all nodes that detect a transmission being sent — independently of whether it comes from blind nodes or not — use the origin as relay for their messages, without sending the REQ_ROUTE message, as a route is already established and communication is assumed to be symmetric. Blind nodes start

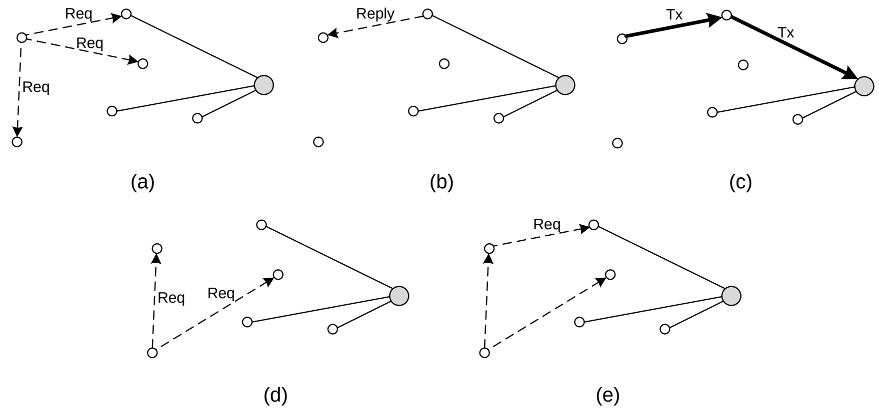


FIGURE 5.9: Proactive tree building in blind nodes.

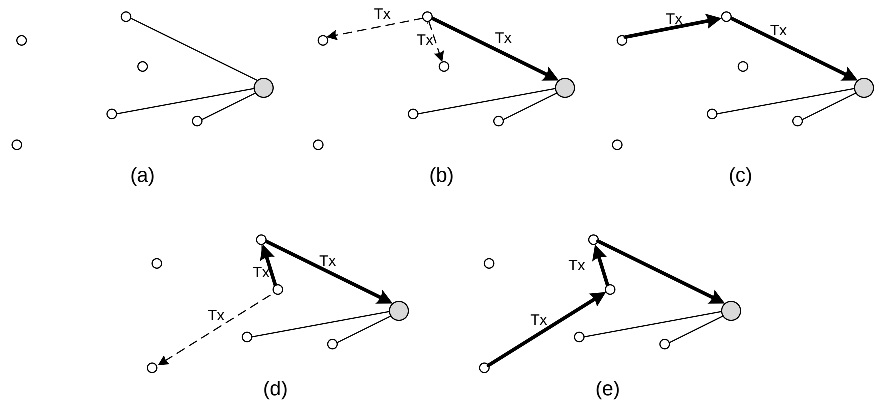


FIGURE 5.10: Reactive tree building in blind nodes.

building opportunistic trees, also making the process epidemic. Figure 5.10 describes the development of this solution, where nodes gradually build trees around the CH once they detect any transmission.

Between proactive and reactive blind node routing, reactive was chosen and implemented. A proactive approach would result in constant flood from nodes without a known CH, further aggravated when the number of nodes increases and weather-related interferences become more frequent. Moreover, as proactive routing requires REQ_ROUTE and ADV_NODE to create routes (once again multiplied by the number of hops), the route set-up time is unknown and once finished, its validity is not guaranteed.

5.6 Environment-aware communication

As previously mentioned, WSNs are sensitive to environmental conditions. The performance of both sensors and radio transceivers rely on the environment and existence of external sources of interference, such as other networks, obstacles, or other sources of electromagnetic radiation. In the particular case of maritime monitoring, there is also a degree of unpredictability regarding the location, weather conditions and deployment size. The urgency involved in monitoring localised events (such as oil slicks) limits the time to set-up, re-program and optimise nodes to an expected set of constraints. Furthermore, the weather unpredictability can lead to inoperative networks, should conditions change more than initially predicted. As such, this section describes a novel environmental-aware adaptive framework that selects network algorithms and adjusts its parameters to better suit the deployment characteristics.

There are two options to the adoption of a WSN to variable environmental conditions: use a general-purpose protocol that can operate in all foreseen scenarios; or continuously adapting the network operation to suit whichever variations may occur. The first option is expected to result in less than optimal operation, as it requires compromises to allow the network to run in both ideal and extreme scenarios. The second alternative can minimise the adverse effects of environment changes by adjusting hardware and/or software parameters. Nevertheless, it requires more complex algorithms, demanding different hardware requirements. Also, as different nodes in a region can use different settings, it is possible that the network starts fragmenting, affecting performance. Eventually, should the weather conditions deteriorate to the extent of making the network unusable, the nodes can simply turn themselves off until the conditions improve.

Adapting the network behaviour relies on a set of pre-defined inputs. It can be seen as a closed loop control system, as shown in figure 5.11. The feedback loop allows further improvements over open loop [166]: disturbance rejection, removal of uncertainties, process stability, reduced sensitivity and improved reference tracking performance. The network parameters are defined according to both network performance metrics and can be matched with known conditions, hence closing the loop with feedback from current settings. Furthermore, sensed data (both from surrounding nodes and from the node itself) can be used to assist the decision process. The adaptive control is designed to be implemented in the CH to minimise hardware requirements in sensing nodes. Moreover, this procedure reduces the autonomy of sensing nodes, hence limiting fragmentation.

5.6.1 Related work

Adaptive mechanisms for WSNs have been explored before to cope with changes. Dunkels et al. [167] proposed a communication architecture that provides an adaptive service to

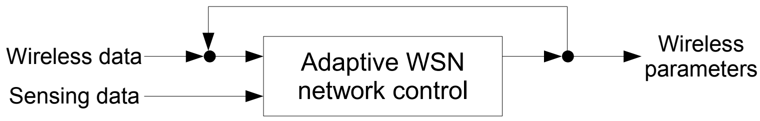


FIGURE 5.11: Simplified control diagram for adaptive WSN behaviour.

support different underlying routing protocols. Their objective was to simplify implementation of protocols by allowing different architectures to work together. Figueiredo et al. [168] applied a hybrid adaptive model that monitors the network conditions and reacts accordingly to save energy. During a monitoring period, if more than one routing discoveries are requested by nodes whilst in reactive mode, the CH/sink will change the routing strategy to proactive and a tree will be built between nodes. The network will return to reactive mode if the CH/sink stops requesting updates to the tree. Sha and Shi [169] proposed a framework and consistency models to manage data quality in WSNs. Their purpose was to maintain data quality while saving energy whenever possible. A similar approach was proposed by Sun [170] and Sun and Cardell-Oliver [171], with a framework based on link quality to adapt or change the routing algorithm. They also enforced a neighbour selection (storing link quality values in a table) at the message origin. The framework ran on a testbed with 10 nodes, hence the link quality table size is small. The authors also mention a monitor module, used to measure current conditions (battery level, temperature, link quality and solar power). Padhy et al. [172] used adaptive sampling and adapt communication rate according to the sensing rate. The communication stack is not affected by sensing, and route decision is solely based on remaining energy.

5.6.2 The environment engine

The environment engine is an independent framework that integrates techniques to adapt routing protocols according to the deployment conditions. The engine runs parallel with the remaining node software and it is a complementary addition to network devices. It gathers information from sensors and communication channel and uses it to decide the best solution to both foreseeable and unexpected circumstances. Any modification to the routing protocol is sent to the network stack, as a set of parameters or, if necessary, as structural modifications to the algorithms. The weather engine framework is shown in figure 5.12.

There are two main modules supporting the environment engine operation:

Environment manager. The manager collects data from sensors and from the different network layers, namely humidity, acceleration, location, number of neighbours, packet reception, error estimation and collisions. This information is used to assess

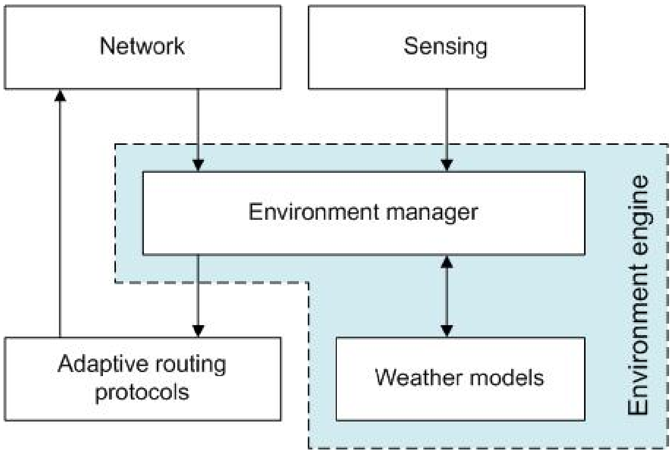


FIGURE 5.12: Environment engine framework and its positioning in a WSN node's architecture.

both network and weather conditions. The estimation is done through a deduction of metrics and figures of merit based on the information gathered, which are exchanged with the environment database. The outcome of the database is then used to adjust the communication stack with the best parameters.

Environment database. The summary from the environment manager is received and compared with stored values to decide the best solution for data transmission across the network. The decision can be based on a known best option from previous set-ups, or by applying dynamic strategies such as analytical models.

Due to the impact that changing parameters may have, parameter changes through the environment engine are performed by the CH and broadcasted to sensing nodes in its surroundings. By doing so, the network maintains routing consistency, with the possibility of a failsafe option for nodes outside transmission range. Nodes will listen to the channel constantly for any eventual CH broadcast. The implications of this option are reflected on the trade-off between current and possible future cluster size and density. Nodes are not able to use the number of neighbour estimation to improve its communication autonomously and proactively. Instead, they rely on the CH to inform them about which strategy to adapt. On the other hand, as complexity of adaptive algorithms can grow beyond microcontroller's performance (thus requiring faster and more expensive hardware), having a single node running the environment engine reduces the network cost.

5.6.3 Adapting network behaviour

When communication environment changes, either due to network or weather variations, the WSN must adapt to work at its optimum. Adaptive behaviour, as defined by

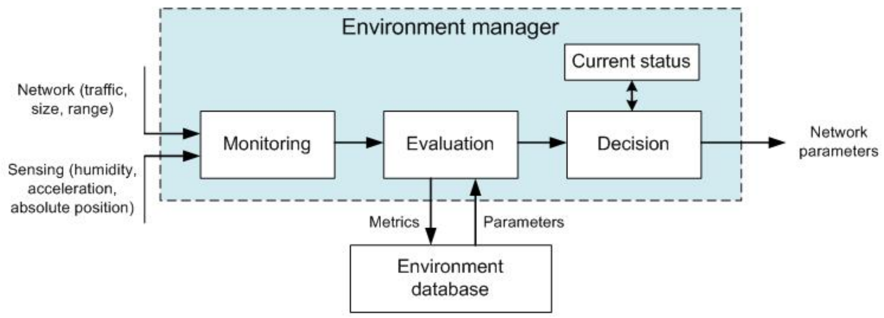


Figure 5.13: Adaptive model for environment manager.

Figueiredo et al. [168], "*(...) refers to the network ability to react to some perceived situation*". The adaptive model used by the environment manager is outlined in figure 5.13. It receives inputs from both network and sensors (e.g. cluster size, estimated range between message origin and CH, humidity and acceleration), which are combined in the Monitoring stage into usable values. These usable values are sent to the Evaluation module to use models that generate specific metrics to be exchanged with the Database. The Database returns a set of parameters, based on either pre-defined or analytical models. These parameters are then sent to the Decision module, which matches them with the Current status and determines whether and how to apply the modifications. The output is then sent to the network stack, divided according to affected layers.

By sending the modifications to the network stack and receiving the status information and updates regarding communication, the manager works in a closed loop with the network stack, measuring the response to the modifications, verifying if the network performance improved and compensating with additional changes, if necessary.

5.6.4 Routing selection rules

The routing strategy for every different situation is decided by attributing scores to experimental results. The previous chapters focused on MAC and Routing layers, thus the adaptive rules will select the algorithms, while considering the full simulation described in this chapter. Other algorithms can also be added, requiring an expansion to the database to define the conditions where new ones outperform those already implemented.

Two different techniques are used to assess the performance of each algorithm. The first solution consists of adding two ratios of packet delivery and average distance between origin and the CH. This is done using equation 5.10. Both message delivery and origin distance ratios are compared to the maximum score amongst the tested algorithms, for each specific (N, H, PL) set. wf is a constant weight factor between the two parameters. The second solution (table 5.2) uses a ranking system that gives points to the three best performing algorithms, both for packet delivery and origin distance. Once again, it is possible to differentiate packet delivery and range with wf, should one of the parameters be considered more important than the other.

$$score(N, H, PL) = wf \frac{delivered(N, H, PL)}{maxDelivered(N, H, PL)} + \frac{dist(N, H, PL)}{maxDist(N, H, PL)} \tag{5.10}$$

Rank	Packet delivery	Range
1	0.5 wf	0.5
2	0.3 wf	0.3
3	0.2 wf	0.2

TABLE 5.2: Algorithm's scores for packet delivery and range.

5.6.5 Adaptive routing decision

Using the simulation results, an adaptive solution for routing is formulated. By combining the results of the different algorithms described in this thesis, it is possible to achieve a trade-off that optimises the network performance to better suit both network and weather conditions. Considering the application scenario of localised maritime monitoring, message delivery is the main objective. To that extent network size, packet delivery and distance between origin and CH are essential metrics. The first value gives an indication of how severe contention and collision between nodes can affect performance. The second shows the amount of information effectively received by the CH. The third provides an insight into cluster coverage area, existence of blind regions and signal degradation. Furthermore, the association between different metrics can be used to give additional insight into operation. For example, if the number of nodes in the cluster increases while the message delivery rate and the mean distance between origin and CH are constant, then the network may have reached the maximum throughput.

Data delivery assumes an even greater priority due to the limitations imposed by unstable conditions. Latency and energy usage are two other important development factors, although their relevance is lower when weather conditions deteriorate. Therefore, their implications on algorithm selection are not considered.

5.7 Summary

Simulations are used to test the performance of algorithms under the expected deployment conditions. Considering the application-specific development that sensor networks rely upon, realistic weather and channel models are fundamental to achieve the trustworthy and significant results. This is of particular interest to the maritime monitoring scenario, where although it is possible to foresee the weather conditions to be found in a random deployment, it is not possible to predict how the network will work unless simulations are performed to try out different algorithms under variable weather.

This chapter described the design of a simulator based on realistic channel and weather models. Additive interferences between nodes and log-normal shadowing channel model are seen in the literature as those providing the most and trustworthy realistic results, hence their adoption during the development stage. Furthermore, the simulator also describes the interfaces between network layers in nodes, providing a framework for the development and implementation of algorithms in sensor nodes. The layers were developed in a structured and modular manner, working closely together to allow cross-layer optimisation of algorithms.

The environment-aware communication engine is a novel framework that combines sensing and communication metrics to optimise the network behaviour under different weather conditions. The engine is based on the assumption that no single algorithm provides optimal results when the level of interference changes. Adjusting parameters (or, ultimately, changing the algorithm itself) improves network performance when compared to a single algorithm alternative. Moreover, as communication works both as an input and output to the framework, it can be seen as a closed loop mesh, where any modification will feed back into the engine, allowing further compensations when needed.

Chapter 6

Simulation results

In this chapter, the performance of cross-layer algorithms will be analysed and discussed, with particular focus on the message delivery, network coverage, collision and latency. The results were obtained by using the custom-built simulator and are based on the assumptions derived in chapters 1, 3 and 4. These results are then used to assess the optimal operation of the environment engine, thus feeding its database.

6.1 Simulation parameters, methodology and assumptions

The application scenario outlines the challenges to be solved, thus providing the parameters and constraints to build a framework. While no previous work provides the same set of challenges that could allow a straightforward comparison, different authors describe solutions that can be combined to support the development of a WSN for maritime monitoring. The OceanSense project [26] used a similar architecture for nodes to the one described in this work, where 18 static nodes are fitted with antennas located 1 m above water level and a 802.15.4 compliant node. As a base station, the authors proposed the use of a resource-rich node. It showed that 2.4 GHz radios can be used at sea, and they measured a lifetime of 1 week with no energy savings and standard AA batteries, which could have been easily improved. Conversely to this thesis, the authors used a standard transceiver with 1 mW transmitting power.

In another maritime project, Cella et al. [27] also used 2.4 GHz radios on a maritime monitoring application, where nodes transmitted at 50 mW (≈17 dBm), a power similar to that adopted in this work. Two other important aspects of their network is the use of a dipole antenna in nodes, limiting the ground plane and reducing any eventual reflection from water (which, as previously discussed, should be minimal or even inexistent), and the placement of the antenna 30 cm above water level.

Parameter	Value
Simulation time	3600 s
Deployment radius	1000 m
Tx time	10 ms
G_T, G_R	2.15 dBi
Receiver sensitivity @ 10^{-5} BER	-95 dBm
N_0	-111 dB
σ	4.6 (2.8 – 6.4) [161]
Antenna height h	0.4 m
κ	1/3000
Time until next wave estimation	1 s

TABLE 6.1: General simulation parameters.

Rajasegarar et al. [25] argued that wave dynamics is an influential factor on communication between nodes. Waves cause misalignment, tilting the antenna, and suggest overcoming this problem through a "*time window of opportunity*". This measures waves (through accelerometers, for example) helping estimating the best moment to transmit data. This is similar to what is perceived in this thesis as transmitting with the node floating on the wave crest to improve p_{Rx}.

Table 6.1 shows a summary of the general parameters for the simulation runs, and table 6.2 presents the different network and weather scenarios being tested with the proposed algorithms. The simulation ran for the equivalent of 1 hour, with transmission windows of 30 seconds and an additional 10 seconds before the CH broadcasting a new ADV_CH packet. As such, each node has a theoretical maximum of 90 updates during runtime.

The simulation ran seven times with each set of parameters, with different node positions between runs. Communication between nodes is dependent on three stochastic processes: node location, path loss and obstruction from waves. Path loss uses a Gaussian zero-mean RV with a pre-defined standard deviation, while the obstruction from waves was made completely random and variable during the simulation run. The displacement was the same for the different algorithms used in each run.

The parameters used were based on a medium size cluster deployed on a relatively large area. A 300 node cluster with nodes distributed across a circular area with 1000 m radius has a density comparable to that of satellite imagery. Smaller network sizes give a worst-case indication of what to expect if nodes start dispersing.

Based on the description from section 5.2, the Physical layer parameters are based on the RFM 2400ER [54] fitted with standard dipole antennas. The transmitter signal is amplified to 18 dBm, with a further gain of 2.15 dBi from the antenna for both transmission and reception [68]. The receiver has a sensitivity of -95 dBm.

Considering the assumptions, there is the need to further detail and adapt the MAC and Routing algorithms previously described. As such, the Routing algorithms were

Parameter	Range
Nodes	50, 100, 150, 200, 250 and 300
Wave height	0.2, 0.6, 1 and 2 m
Path loss exponent η	2, 3, 4 and 5

Table 6.2: Environment-specific parameters.

re-designed in a cross-layer manner, based on the modules implemented in the simulator framework.

The simulation uses a global discrete, pseudo-real-time clock. Clock drift was not implemented, nor variable data rate. Conservative values were used for data rate. Each packet takes 10 ms to be transmitted, corresponding to over twice the period that a 128 bytes long packet (the largest packet size achievable with IEEE 802.15.4) need to be transmitted. As previously argued, the ratio between the packet time and the total transmission time (as advertised by the CH) is more important than the actual packet size in regards to contention.

One important addition to the communication process is the handshake mechanism. Before transmitting data, nodes and CH exchange RTS/CTS-like messages to guarantee that there is line-of-sight between them and that the received signal is strong enough to decode the message correctly. By doing this, there is at least a three-fold increase in the number of sent packets. The handshake process is done at Routing level to allow the use of distance and remaining energy based metrics previously described.

Single-hop routing is used as a basis for performance comparison between algorithms. SH is a simple and straightforward algorithm that can be used since nodes are expected to be within direct communication range of the destination. Furthermore, its simplicity results in minimal latency, and the low use of bandwidth minimises collision and hidden node problems. However, this is the case of an expected network operating under clear weather, and as conditions get worse SH's performance is expected to deteriorate. Greedy routing represents the other extreme, where nodes choose the closest intermediate to relay messages. This allows transmitting nodes to deliver each packet with the highest SINR, thus reducing errors and interferences. SH and GR algorithms represent extreme opposites, whereas two-hop algorithms represent balanced alternatives.

Four parameters are used to measure algorithm's performance: sum of packets correctly delivered to the CH, collision count, latency and distance between origin and CH. They represent message delivery rate, their delay, and the real cluster range under different weather conditions and network set-ups.

The results are divided in three main sections: single-hop, multi-hop and opportunistic routing. Single-hop provides the grounds to evaluate how the simulator performs versus those achieved in previous chapters. Multi-hop results are compared with those of SH to assess if and under which conditions they deliver better results. The addition of opportunistic routing from blind nodes is also expected to improve multi-hop results, when comparing with SH. Therefore, the third result section will compare opportunistic results with those achieved by SH.

The detailed tables with results are provided in appendix 2.

6.1.1 Output metrics

The basic aim of WSNs is data gathering and information retrieval for further analysis. The more information is available, the more accurate the results become. As such, packet delivery is a fundamental metric to assess network performance. In addition, other outputs contribute to a deeper understanding and comparison of network performance using different algorithms and tuning options, particularly if packet delivery is lower than expected:

Packets generated. The total number of packets generated across the network. It includes route requests and advertisements. This metric provides an insight into bandwidth usage and contention estimation.

Data packets generated. This variable counts solely the number of data packets generated by nodes. This leads to data and overhead packet ratios with different algorithms and a distinction between set-ups.

Data packets delivered. The number of data packets delivered can be related to the number of packets generated (both data and overhead) to provide an estimation of lost packets, thus algorithm performance.

Data packets relayed and received by the CH. Knowing the number of intermediate hops between origin and CH provides a better understanding of how often multi-hop algorithms use alternative routes with different weather conditions.

Collision count. The number of packets colliding, independently of being data or overhead packets, leads to an analysis of the network capacity.

Mean packet latency. The time it takes for a packet to be sent across, from the instant the origin starts transmitting it, until the time the CH receives it correctly. Combined with the number of data packet received by the CH, it allows an understanding of back-off mechanism performance.

Mean distance between origin and CH. Knowing the distance between origin and CH gives an understanding of the network coverage achieved when the weather conditions change, and what influence the algorithm selection has on the network performance.

Mean remaining energy. The energy remaining between all nodes in the network is the basis for estimating the network lifetime.

The combination of the above outputs gives additional information regarding the performance of network and algorithms. In addition, the understanding of a specific issues may not be straightforward from single outputs. One example is packet delivery, which can be conditioned by network size, weather, collisions, number of hops, or a combination of these. Ultimately, evaluating the performance of an algorithm demands a combination of all the above outputs, by establishing an order of relevance to those that are considered more important during the scenario description.

The simulator also demands specific and application-related assumptions to produce the most realistic results. These are derived from the description in chapter 1:

Network deployment and displacement. The nodes are thrown randomly from aeroplanes, helicopters or nearby vessels. Although a completely uniform distribution is desirable, it is unlikely to occur. As such, a completely random network displacement is considered. Nevertheless, CHs are in smaller number and expected to fully cover the region to be sensed, therefore they can be deployed with a degree of accuracy. Considering this, the simulations use a single cluster with the CH in the centre and the sensing nodes randomly displaced around it in a circular area.

Network size. To maintain a resolution comparable to that of radars in satellites, nodes must be placed less than 100 metres apart. As such, it is possible to find over 200 nodes per cluster when the transmission range is 1000 metres in optimal conditions.

Weather. The weather conditions can change significantly during the operation, affecting communications. Moreover, reprogramming nodes is unlikely to occur before each deployment. Although there are thresholds in which the network is realistically usable, there is a degree of freedom to which protocols respond best. The influence of weather on the communication between nodes is the sole focus of this thesis, while any considerations regarding weather effects on sensing are beyond its scope.

Mobility. Despite the constant movement of water, nodes are expected to drift in sympathy with each other. As mentioned in chapter 1, spills expand in a predictable pattern, therefore nodes are also expected to slowly drift apart, with little relative movement between them. For these reasons, the network is considered to be static during the simulation runs.

Medium Access Control. Node's communication is reactive, requiring an initial query from the CH to start transmitting. The random node selection and retransmission scheme with multiple retries is used due to the performance improvement and overall simplicity. Time selection with multiple retransmission is random and with no skewness.

Routing. To promote a detailed comparison, the four schemes (single-hop, Greedy, SRD and MRD) presented in chapter 4 are implemented.

Communication channel. Nodes always transmit using the maximum P_{Tx}. This decision is motivated by the results obtained in chapter 3. Although a variable transmission power could save energy and minimise exposed terminal problems when using multi-hop, the use of maximum P_{Tx} can help reducing losses and collisions between nodes.

Duty cycle and sleep schedules. When nodes use single-hop, it is possible to put them to sleep once they receive advertisements from the CH and have a selected transmission slot. However, since it is not always possible to maintain static routes in multi-hop due to irregularities and connectivity loss, nodes must listen to any incoming request, reducing battery lifetime and increasing overhead.

Simulation running time. Being reactive and controlled by CHs, the network behaves consistently throughout time and its performance is dependent on environmental parameters. Results from a fixed period of time are considered valid for the whole lifetime.

Energy. Details regarding energy storage devices, discharge rate or recharging methods are beyond the scope of this research. A general-purpose discharge model is used, and the total energy drained by the network during each run is measured.

6.2 Single-hop results

Single-hop is the simplest and most straightforward routing strategy inside a cluster. It provides an insight into how transmissions are influenced by weather changes. With clear weather and flat sea the Tx range is maximum and there are no blind spots caused by waves, therefore this scheme is expected to provide the best results out of any algorithm, as long as the nodes are within range of at least one CH. As the conditions get worse, single-hop will show how changes in path loss exponent (PL) and number of blind spots due to wave height affect communication.

Different metrics are used to quantify the performance. Packet delivery is an absolute value of the number of packets correctly received by the CH. Estimating the theoretical maximum and combining it with simulation scores leads to conclusions regarding the expected and achieved delivery rate. To improve the understanding of transmission rate, node visibility and packet loss, the observed collision rate is measured and analysed. The mean distance between the packet origin and CH shows how path loss exponent and waves attenuate transmission and how it relates to distance between sender and receiver.

6.2.1 Packet delivery and range

Figure 6.1 shows the packet delivery variation with different PL, H and network sizes. For visibility purposes, the results were divided according to the path loss exponents, and each chart contains the results achieved with a single PL and different H values (described in the legend). There is an almost linear increase in delivery rate with the number of nodes for a given set of weather conditions. On the other hand, the successful packet delivery decreases as the weather gets worse, as visible through the sequence between charts 6.1(a) and 6.1(d). The increase in PL reflects a decrease in range, hence number of nodes directly visible to the CH, which results in less than 20% of correctly delivered packets for PL=5, when compared with PL=2. Concurrently, the increase in wave height also reduces packet delivery. Wave height does not relate to the distance between origin and CH (as described in chapter 1); instead, it relies on the height of receiving node to achieve it.

The successive reduction in packet delivery with the worsening of weather conditions is related to the decisions while setting up the network algorithms. To allow a reliable comparison between algorithms and the effects of weather conditions, algorithms are reactive and only after a ADV_CH packet has been received nodes prepare a new message to be sent. As the transmissions originating from the CH are as vulnerable to interferences as those of nodes, ADV_CH packets have the same guarantee of being correctly received by nodes. As such, the probability of the CH receiving correctly a message from a node becomes p_{Rx}^2 for $h > H$, due to the two reception stages involved.

It was shown in chapter 3 that channel listening and retry provide correct delivery of over 85% of packets in a cluster with 1000 nodes, when considering optimal weather conditions. The smaller cluster sizes simulated lead to a lower collision rate due to hidden and exposed terminals, thus the number of delivered messages approaches even further the theoretical maximum. An insight into packet collision rate with different weather conditions (shown in the charts of figure 6.2) reflects how this measure changes for the different simulation parameters, and how the two variables (PL and H) influence the performance. When $H = 0.2m$ and PL=2, the collision rate follows what was described in section 3.4. As H increases, the collision rate increases with it, since waves stop nodes from listening to ongoing transmissions. Nevertheless, as wave height keeps increasing, the number of nodes receiving the ADV_CH message decreases, hence lowering the collision rate. Conversely, the number of collisions decreases while PL get higher, essentially due to the SINR variations and number of nodes within range. Overall, the combination of PL and H result in relatively constant evolution of collisions

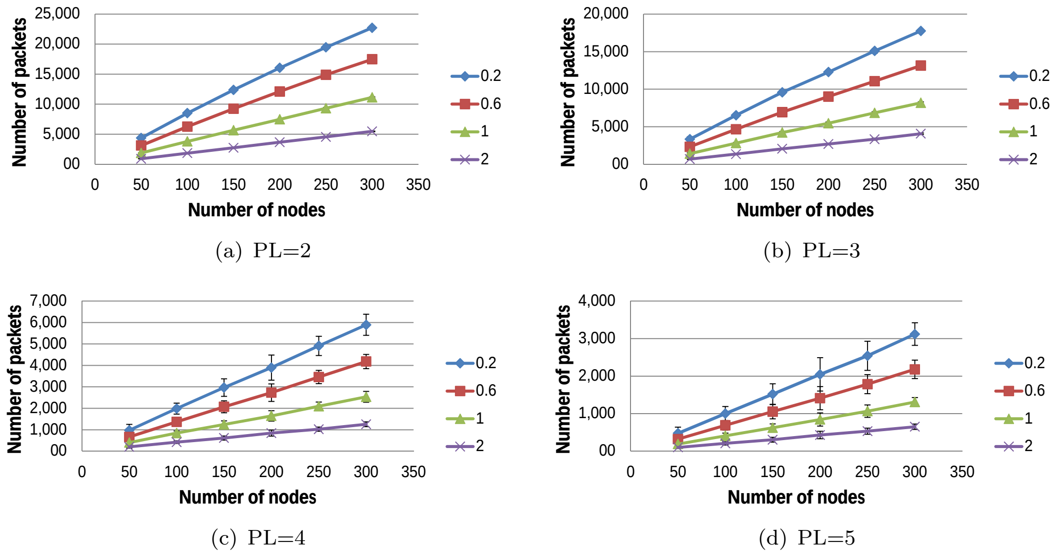


FIGURE 6.1: Packet delivery for SH routing with PL between 2 and 5, and H between 0.2 m and 2 m.

with the increase of nodes in the network, and the highest variation is due to bad weather combined with small network size, leading to a lower collision rate.

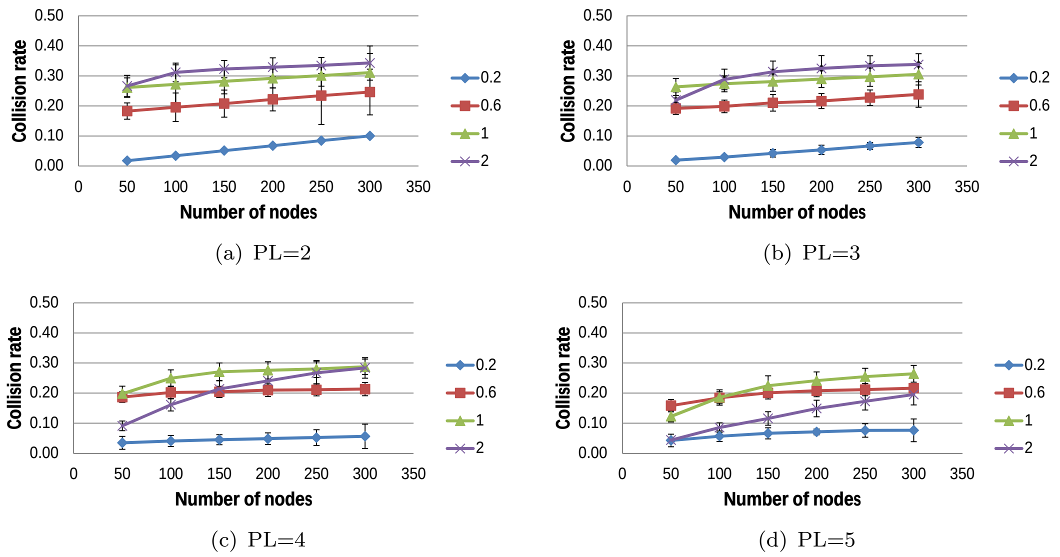
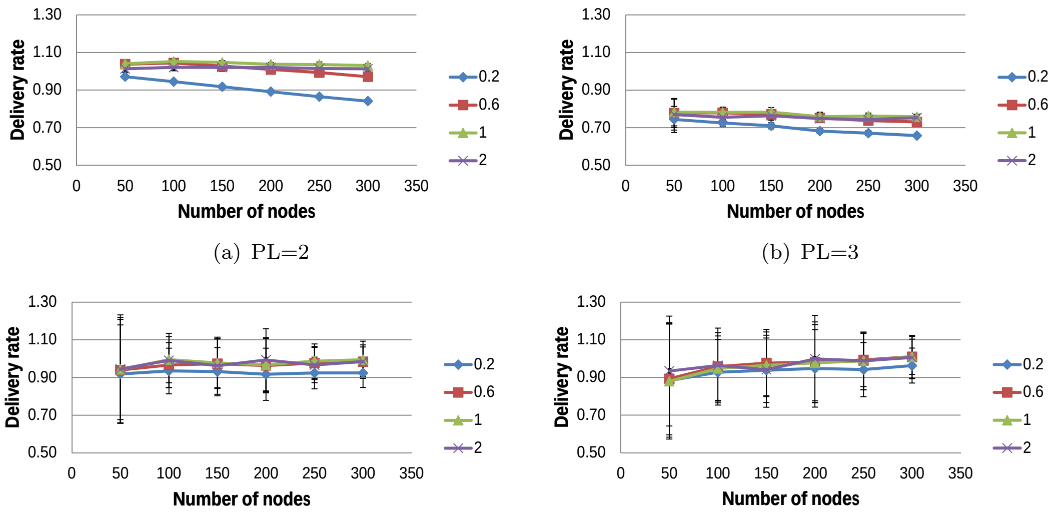


FIGURE 6.2: Collision rate for SH routing.

The drop in packets delivered when the weather changes is expected. It can be calculated using equation 6.1, derived from equations 5.2 and 5.4. The ratio between estimated and simulated delivery is shown in figure 6.3. Simulation results are, for most of the conditions, within 90% of the theoretical values. With PL = 2, the simulation rates are higher than estimated, due to randomness of the network displacement and the increased collision avoidance not accounted in the model — although the sensitivity is

-95 dBm for a 10^{-5} error rate, nodes can detect a transmission at lower sensitivity and avoid collisions. The lack of collision estimation in the theoretical calculation is mainly visible with PL = 2 and $H = 0.2$, where the collision rate increases with the network size, leading to a constant decrease of the simulation results. When the PL exponent increases (figures 6.3(b) to 6.3(d)), the difference between maximum and minimum achieved over estimated delivery rate is smaller and less dependent on the number of nodes, where variations are commonly below 10%. The largest difference in these values occurs when the $H < h$, since it is estimated that a higher number of nodes are within transmission range of the CH, whereas in simulation it was the most affected by hidden terminal problems.

$$\sum \text{Delivered} \approx \frac{0.4}{H}\, 80^{\frac{5.88}{\eta}}\, N \frac{T_{sim}}{T_{CH}} \tag{6.1}$$



(a) PL=2 (b) PL=3

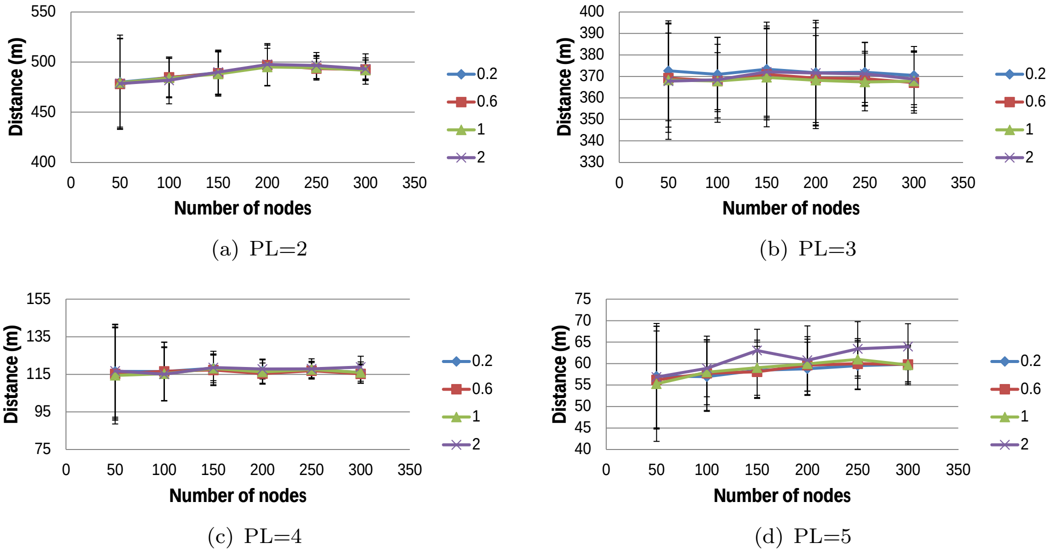
(c) PL=4 (d) PL=5

Figure 6.3: Simulated packet delivery as a fraction of theoretically estimated rate.

6.2.2 Mean distance between origin and CH

One of the issues raised from the results is the network coverage and how the different parameters affect packet delivery for nodes at different distances to a CH. Figure 6.4 shows the mean distance between message origins and CH, for correctly received messages. As expected, the mean distance decreases with the increase in path loss exponent. In the worst case of $PL = 5$ the range is below 70 metres, even when considering standard deviation.On the other hand, attenuation due to waves does not influence the mean distance: all nodes are affected equally, independent of their location, since the attenuation through water is always too high to allow a correct reception.

By combining the mean distance scores with packet delivery and collision estimation, it becomes visible that collisions and blind nodes also affect the network evenly. While variables change, the range between maximum and minimum distances is always below 12%.



(a) PL=2 (b) PL=3

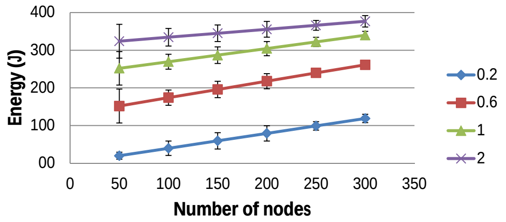
(c) PL=4 (d) PL=5

FIGURE 6.4: Mean distance between origin and CH, in metres.

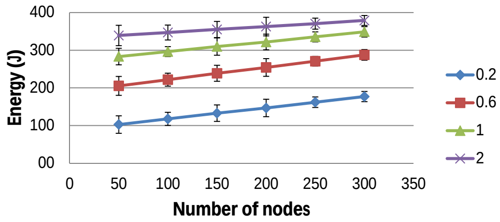
6.2.3 Energy

When nodes receive advertisements from the CH, they decide autonomously when to send their data. In the message, the CH includes information regarding the node's minimum and maximum reply time until the next broadcast. Since nodes are only expected to transmit once during that period T, they can turn off the transceiver for the remaining time to save power, only switching it on to send out their collected data. When a node does not receive any advertisement, its receiver remains constantly on, awaiting any ADV_CH. Although the node would be in idle listening for most of the time (which in practice represents a lower power usage, when compared with receiving power), the simulation uses a $P_{idle} = P_{Rx}$.

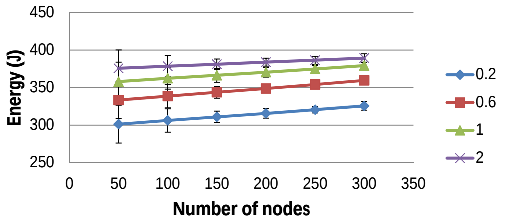
Figure 6.5 summarises energy usage per node for the different simulated conditions. When $PL = 2$ the range of energy consumption for the different wave heights is high (between 19.8J and 323.9J for a network of 50 nodes), whilst it becomes smaller (between 347.9J and 384.3J for 50 nodes) when $PL = 5$. This is a consequence of either an increase in number of nodes or weather deterioration. On one hand, as the number of nodes increases, so does the number of back-offs and retries. On the other hand, as the weather gets worse, fewer nodes receive the CH broadcast message. In both cases, they will listen to the channel for longer, until they send data or receive an advertisement, respectively. In the extreme case a node does not receive any advertisement during the entire simulation, thus it remains constantly listening. In such case, the total energy used is 392.04 J per hour. In such conditions, a standard set of batteries with 20 kJ of stored energy would last for 51.2 hours until the node stops working. Channel listening before transmission is a quick process that in the overall energy budget represents a small fraction of it. One transmission demands 4.4 mJ, while channel listening requires 0.11 mJ. One interesting aspect to research further is the use of duty-cycles and energy-aware MAC layer to reduce energy consumption for the worst-case situation.



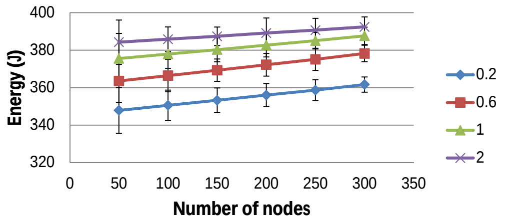
(a) PL=2



(b) PL=3



(c) PL=4



(d) PL=5

FIGURE 6.5: Energy usage for SH routing.

6.2.4 Discussion

Using single-hop routing provides the basis of comparison for the implemented algorithms. The simulations show that its packet delivery performance approaches the ideal maximum when the weather is flat. This proves that SH routing is a solution for clear weather, when sensing nodes are within range of at least one CH. There is a steep decrease in packet delivery with the degradation of weather conditions. In such conditions, nodes lose line of sight towards the CH, therefore multi-hop is expected to outperform SH. One possible solution to the problem is the use of periodic broadcasting (possibly resorting to flooding or gossipping for proactive multi-hop routing) to increase packet delivery when nodes are not subscribed to any CH.

The losses due to collisions with optimal conditions are as expected, considering the number of packets being exchanged in each cluster. When the weather gets worse, packet collision also increases. Energy consumption per node with clear weather is also the smallest achievable, as sleep states can last longer and relaying is non-existent. The variations in collision rate lead to the conclusion that there are factors involved (beyond the number of nodes) in its estimation. Location, PL and random obstruction from waves affect line of sight between nodes, reducing network connectivity. Latency was not included in SH analysis, as direct communication delays are always the smallest of any algorithm. In ideal cases, latency depends solely on the propagation and transmission time.

The mean energy used by nodes is proportional to the increase in path loss exponent. The algorithm used only allows nodes to go into sleep mode once they have a known transmission time. If, on the other hand, nodes do not receive the ADV_CH message, they remain listening to the channel. Although transceivers require less current while in idle listening, the values used are the same to predict a worst-case situation where the network lifetime is the smallest.

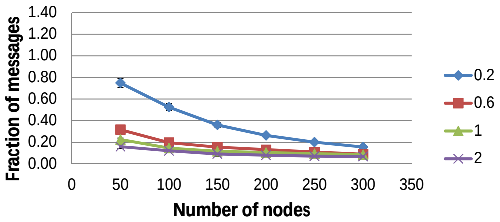
6.3 Multi-hop results

Single-hop routing serves as a static rule for algorithm comparison. It is the simplest alternative that can be used inside a cluster, providing reliable and comparable scores. As previously shown, SH's limitations become more evident when weather conditions get worse. Multi-hop routing algorithms aim mainly at reducing these limitations by using intermediate nodes. Therefore, a comparison between SH and multi-hop serves as a mean to assess the advantages and to what extent increasing complexity is beneficial to network's success.

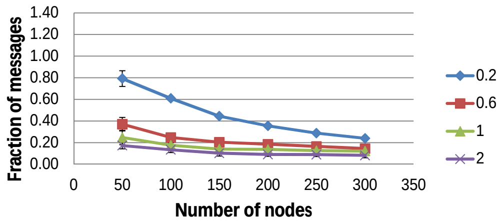
6.3.1 Greedy routing

Greedy (GR) algorithm uses the knowledge of node's location to find the most suitable relay, solely based on self-interest. The premise to this is that transmission costs more that listening and reception, especially when origin and destination are far from each other. This same principle can be used for communication: shorter distances improve SINR, hence the packet decoding success rate is higher, despite any simultaneous but more distinct transmission. On the other hand, the increase in overhead caused by finding the best route needs to be compensated, particularly in central nodes, as previously shown.

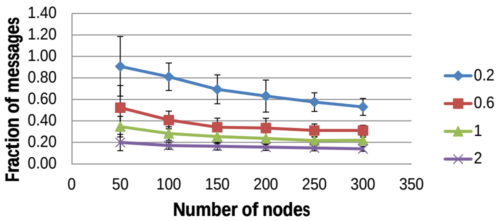
Comparing with single-hop delivery rate, Greedy consistently achieves lower scores overall, as shown in figure 6.6. The results compare GR and SH with back-off and multiple retry MAC layers. As expected, the relative success rate decreases as the number of nodes in the cluster increases. The higher number of nodes results in a higher number of replies to route requests. Despite the efforts to minimise unnecessary replies, the number of potential relay candidates is dependent on weather conditions and visibility between them. Each candidate stores all REQ_ROUTE messages (if it is in a position to relay messages), and discards them if another node replies before. The reply process must be quick enough to ensure that no wave appears in the meantime, while still leaving enough time for the origin to send data. It was decided that the complete process (from REQ_ROUTE to the end of the data transmission) should last less than 100 ms, otherwise the transmission is dropped. This can cause additional collisions during the ADV_NODE stage due to the potential number of replies from potential relays in large networks.



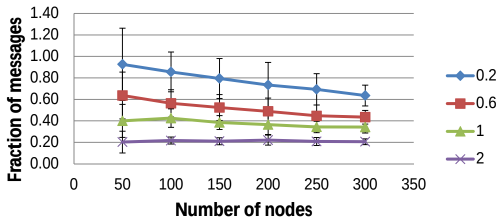
(a) PL=2



(b) PL=3



(c) PL=4



(d) PL=5

FIGURE 6.6: GR packet delivery as a fraction of SH.

The extreme paradigm of the implemented GR algorithm leads to the worst case scenario of transmitted packets. The number of hops for each message is the highest, as the algorithm searches for the shortest transmitting distance between nodes towards the CH. The outcome is an increased overhead, further aggravated by missed reply packets. The added overhead impact and missed replies and additional REQ_ROUTE can be estimated through latency, as shown in figure 6.7. The significant increase in latency when H increases results from the multi-hop strategy adopted: intermediate nodes only drop packets when they either transmit them or receive a new ADV_CH. Combining this with the low route availability leads to delays that can reach over 80 seconds. Although it would be simple to implement a mechanism to drop old messages and advertisements, they were left intentionally. Another alternative would be to implement a priority queue, where messages were forwarded according to importance or timeliness, combined with a packet dropping mechanism.

Collision rate is high, as shown in the charts of figure 6.8, due to the high number of packets exchanged between nodes. Despite this, there is a reduction in collisions due to the shorter range between sender and receiver when conditions deteriorate. The improved SINR between closer nodes, along with a lower overall transmission count and the algorithm's flexibility, leads to a smaller collision rate than that achieved with SH.

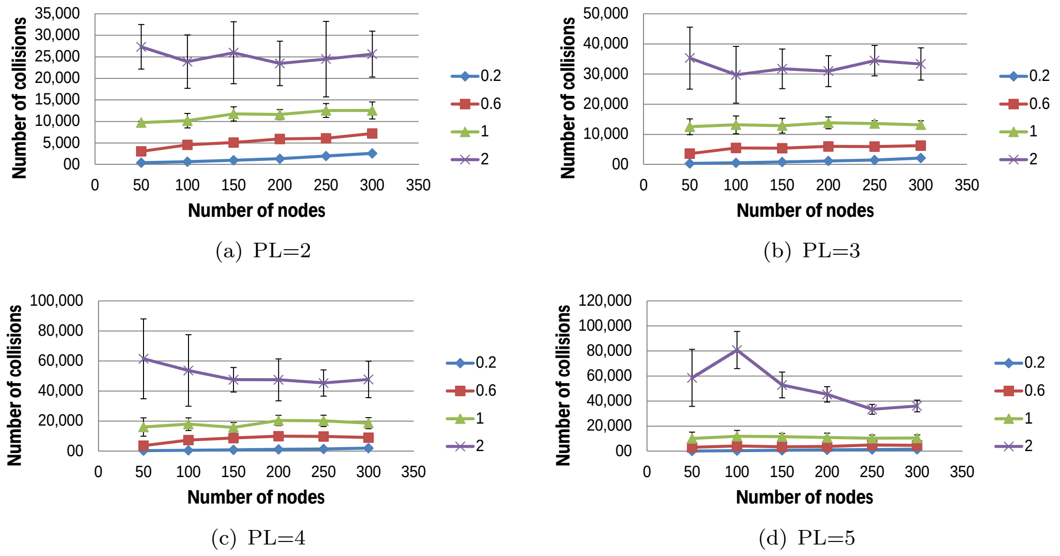


FIGURE 6.7: Network latency with GR routing.

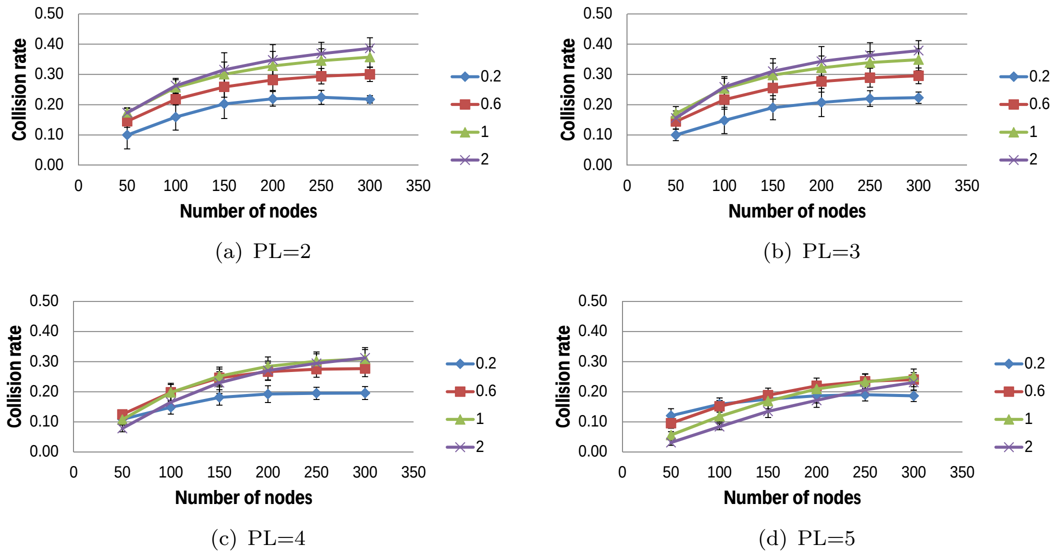
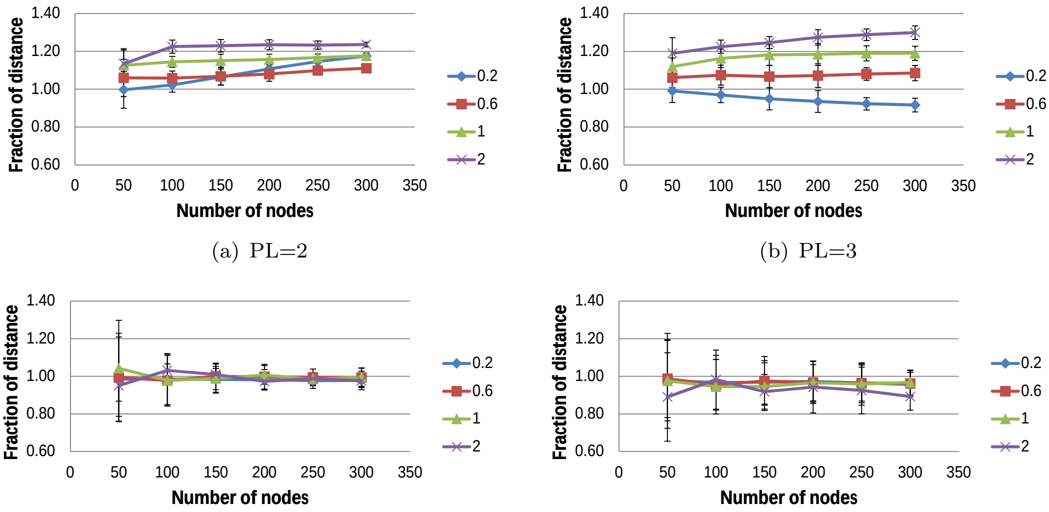


FIGURE 6.8: Collision rate as a fraction of correctly received messages by the CH, for GR routing.

The performance of GR is also assessed through the distance between message origin and CH. Due to the number of intermediate relays, messages generated in peripheral nodes have a higher probability of loss due to collision. However, as each message from peripheral nodes is sent to a close neighbour instead of the more distant CH, the higher SINR can somewhat compensate for the packet loss probability. As shown in the charts of figure 6.9, the mean distance between message origin and CH actually increases, when compared with that of SH. The successive forwarding of each message result in a lower collision rate on a per-hop basis. This is true for low PL values (PL=2 and PL=3) and

$H > h$. For higher values of PL, the results become similar to those of SH, since relaying decreases.



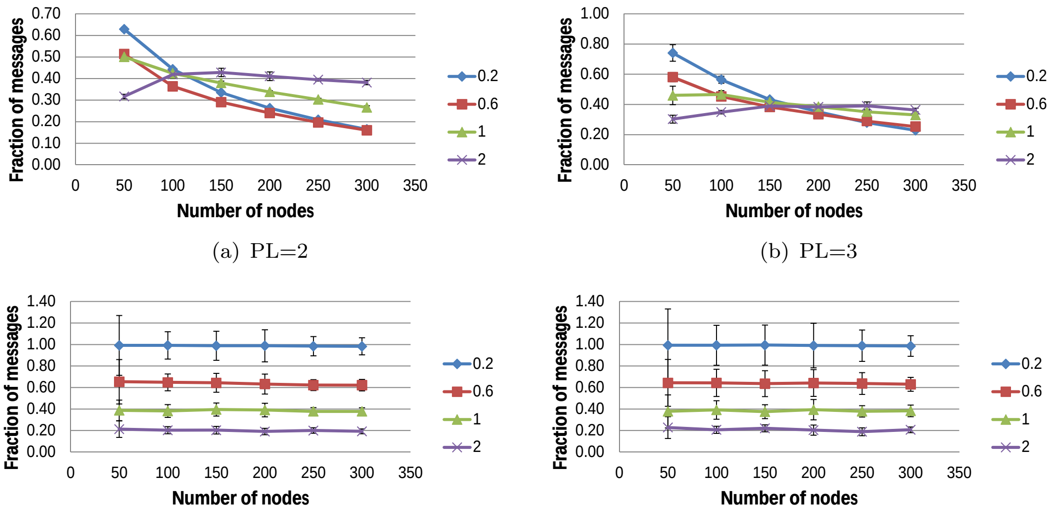
(a) PL=2 (b) PL=3 (c) PL=4 (d) PL=5

FIGURE 6.9: Mean distance between origin and CH for each received message as a fraction of SH.

6.3.2 Two-hop results

Two-hop strategies aim at balancing the packet delivery while keeping a similar performance to that of SH. By limiting the maximum number of relaying nodes the results should approach those of SH with clear weather, while achieving better scores when conditions deteriorate. Furthermore, it is important to analyse the differences when using single and multiple relays, and its impact of redundancy in the overall performance. The use of multiple relays also demands a different approach towards relay candidate reply strategy. With SRD, nodes delete the REQ_ROUTE message immediately once another candidate replies. If MRD is being used, nodes cannot delete it until they listen to at least three replies. Although this process is straightforward for clear weather and medium to large size networks, it can cause unexpected results when the number of potential relays is less than 3. The number of relays was left constant during this simulation to analyse its impact.

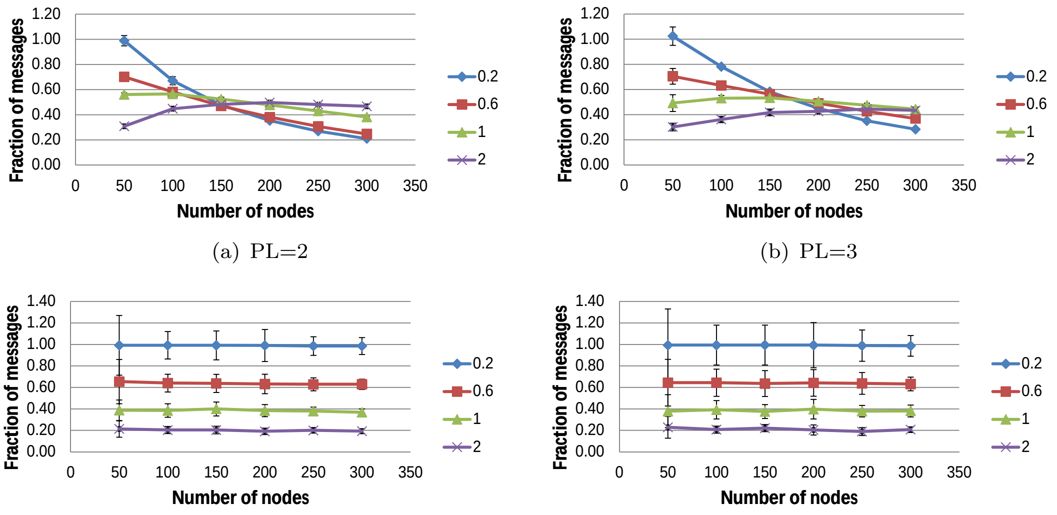
As the number of hops is limited to a maximum of two, overhead, packet losses and consequently latency are also lower than those of GR. Packet delivery, as can be seen in the tables of figures 6.10 and 6.11 (for SRD and MRD, respectively) is comparable to that of SH for clear weather. Nevertheless, delivery deteriorates quickly with any obstruction or increase in PL. With higher PL exponents both SRD and MRD achieve similar results: MRD does not manage to find multiple routes with the same frequency as it does with clear weather, making it similar to SRD.



(a) PL=2 (b) PL=3

(c) PL=4 (d) PL=5

FIGURE 6.10: SRD packet delivery as a fraction of SH.

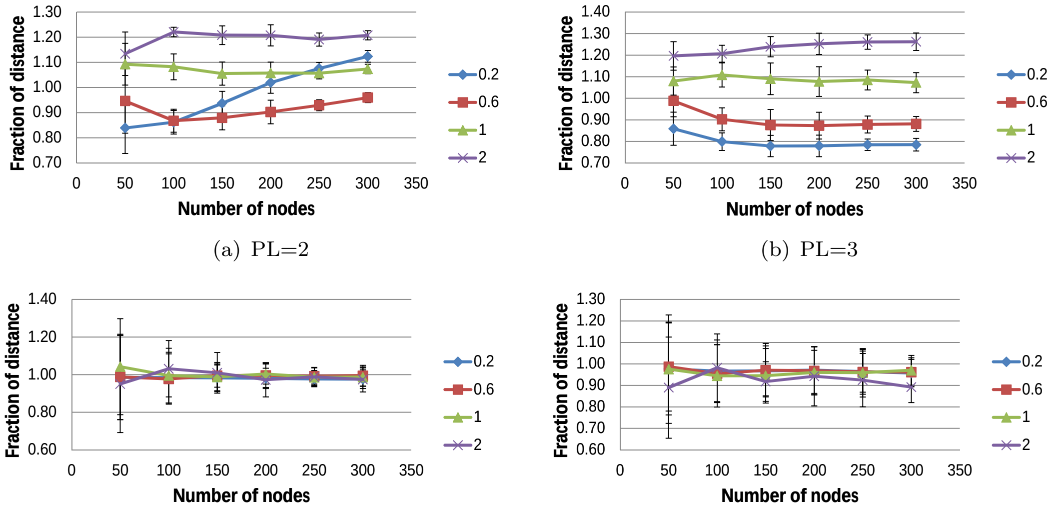


(a) PL=2 (b) PL=3

(c) PL=4 (d) PL=5

FIGURE 6.11: MRD packet delivery as a fraction of SH.

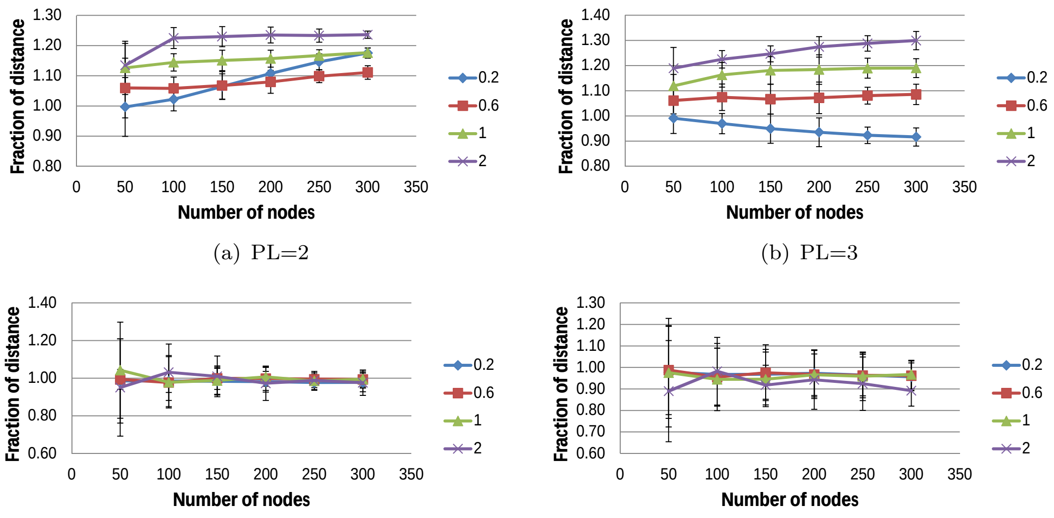
Contrary to packet delivery, the use of two hops in peripheral nodes has positive impact on the mean distance between message origin and CH, as visible in figures 6.12 and 6.13. Both algorithms show a consistent increase in mean distance ratio (when compared with SH), with an advantage for MRD algorithm when PL< 4. For higher values of PL, the mean distance is similar between SH, SRD and MRD. The two-hop areas (as displayed in figure 4.7) were kept constant, independently of differences in weather. For higher PL values, where the maximum transmission range is lower than the inner area, the two-hop algorithms effectively behave as single-hop. The lower packet deliveries seen in both algorithms when the waves are higher than the antenna are due to a specific implementation decision: like it was decided for GR, nodes cannot drop packets until they either receive a new ADV_CH or transmit what they were requested to forward. As with GR, it would be simple to improve performance and make it similar to SH, through periodic buffer reset or using priority queueing.



(a) PL=2 (b) PL=3

(c) PL=4 (d) PL=5

FIGURE 6.12: Mean distance between origin and CH with SRD routing as a fraction of SH.

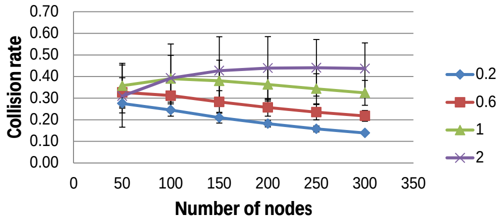


(a) PL=2 (b) PL=3

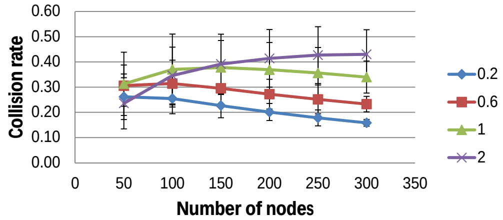
(c) PL=4 (d) PL=5

FIGURE 6.13: Mean distance between origin and CH with MRD routing as a fraction of SH.

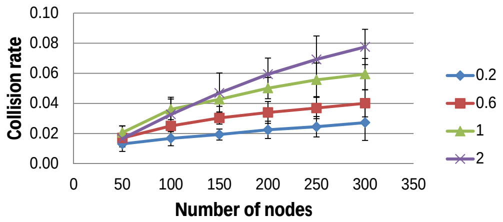
By limiting transmission to two-hops, collisions are also limited. In theory, the relaying process in an uniformly distributed network with a fixed relaying area has a predictable maximum number of exchanged packets. As such the collision rate is also estimated. As can be seen in figures 6.14 and 6.15, there is a higher collision rate than with SH for low PL exponents. Collision rates are also higher than those with GR routing under the same conditions. Relay requests and multiple ADV_NODE for each ROUTE_REQ are responsible for the higher number of packets when compared with SH. With higher PL exponents, as there is no relaying, the collision rate reduces significantly to values below 1%. This is due to the combination of two-hop effectively becoming single-hop routing and the low number of packets in contention.



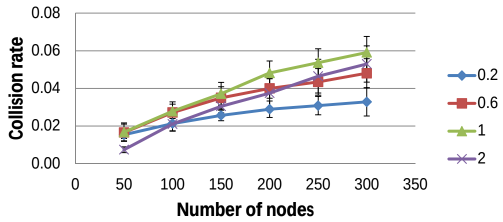
(a) PL=2



(b) PL=3

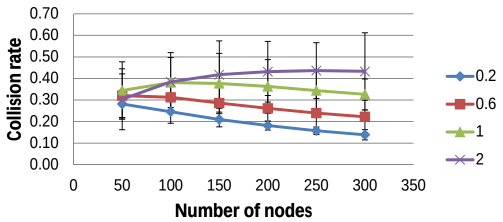


(c) PL=4

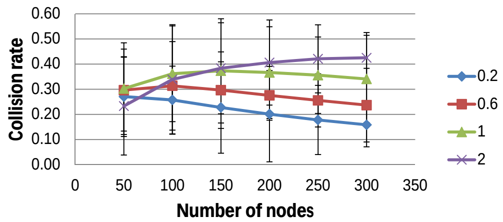


(d) PL=5

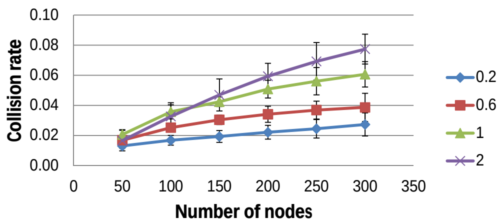
FIGURE 6.14: Collision rate for SRD routing.



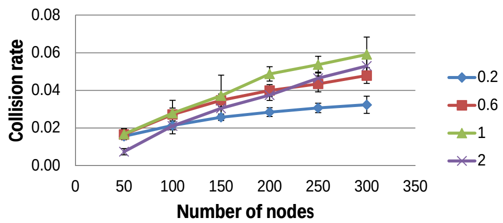
(a) PL=2



(b) PL=3



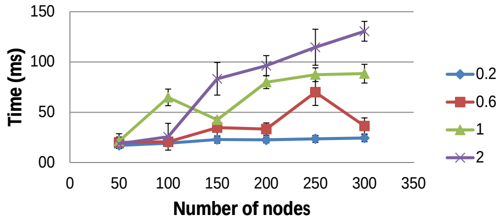
(c) PL=4



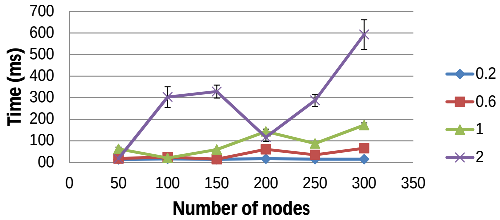
(d) PL=5

FIGURE 6.15: Collision rate for MRD routing.

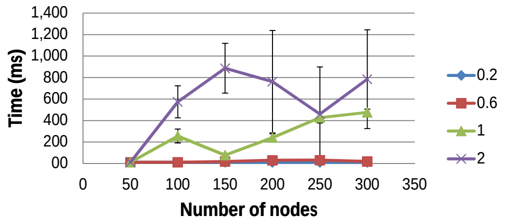
Another important limiting aspect of multi-hop routing is latency. When using GR the latency increases exponentially with the number of nodes. Using two hops results in a latency comparable to that of SH, as visible in figures 6.16 and 6.17. The values, despite being a mean of seven runs, can be highly variable when the number of nodes changes, particularly for SRD. When waves block the transmission, intermediate nodes must back-off and retry sending the messages at later times. For that reason, latency increases with wave height, also becoming more random. Nevertheless, the mean latency is always below 1 second for any given set of conditions, a highly acceptable value for the application scenario described.



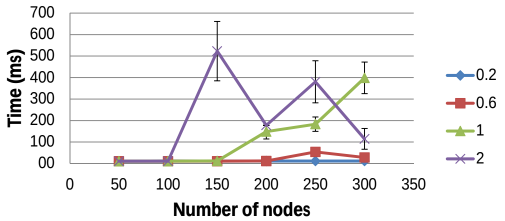
(a) PL=2



(b) PL=3

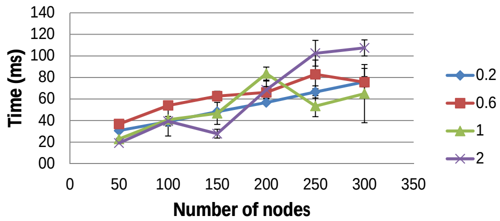


(c) PL=4

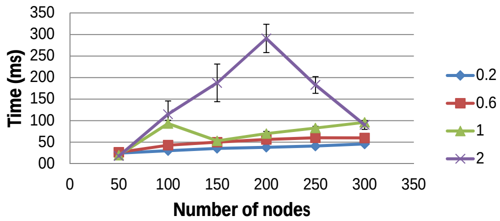


(d) PL=5

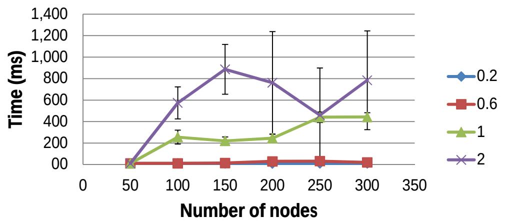
FIGURE 6.16: Network latency with SRD routing.



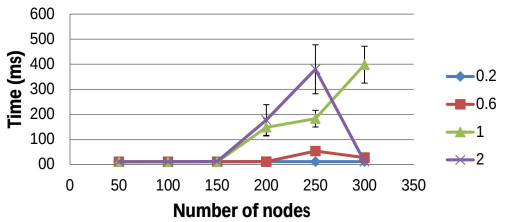
(a) PL=2



(b) PL=3



(c) PL=4



(d) PL=5

FIGURE 6.17: Network latency with MRD routing.

6.3.3 Discussion

Greedy routing is the extreme opposite of SH. Its primary objective is to minimise communication distances while saving energy. However, the implemented algorithm did not minimise P_{Tx} and the transceivers was working continuously. Every transmission was done with maximum P_{Tx} (following the results of chapter 3) to reduce collisions. One collateral effect of this decision is the improved SINR in receiving nodes, resulting in a lower BER and higher probability of receiving the packet correctly. However, as the number of exchanged packets increases with the number of hops, the probability of collisions is still high, hence the delivery is always lower than that achieved with SH.

Latency also increases with the number of hops. Higher latency, along with the number of hops, increase buffered messages. As the algorithm re-sends a REQ_ROUTE message until a candidate replies, latency increases with wave height and frequency. Higher and more frequent waves limit the number of visible neighbours which, combined with the limitations in PL, reduce the number of nodes to the point where no possible relay (or even the CH) receives the request.

Greedy shows that multi-hop can offer advantages over single-hop, despite the increased overhead and lower general performance resulting from the extreme nature of the implemented solution. A more balanced outcome was expected from the two-hop alternatives. Restricting the number of hops provides better and more consistent results than GR for a wider cluster size, while allowing more flexibility than SH. During the simulation runs, the algorithms kept the same set-up regarding the relay area and number of relays with MRD. Although this generated non-optimal results, it provided a reliable comparison.

Packet delivery with both SRD and MRD is similar to that of SH when the waves are lower than the antenna. As the weather deteriorates, the delivery rate also decreases. On the other hand, MRD shows improvements over SH in mean distance between origin and CH. These two scores, delivery rate and mean distance, lead to the conclusion that peripheral nodes become more successful with this scheme. Latency is another factor where two-hop routing shows its advantage. Although always higher than that of SH, the maximum latency is a fraction of what was achieved with GR and does not increase significantly with the number of nodes. One side effect of low latency is the smaller buffer requirement.

Overall, packet delivery with multi-hop is lower than that of SH for most conditions. Nevertheless, results are promising due to the mean distance between origin nodes and CH, and in the case of two-hop, the effects in collision rate and latency are controlled.

6.4 Opportunistic routing results

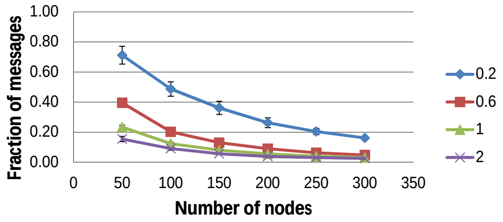
The inclusion of opportunistic routing allows nodes to transmit to the CH when they do not receive an ADV_CH message. This is one of the alternatives to improve packet delivery across the network when the weather affects its operation. The opportunistic routing (described in chapter 5) approach was introduced in GR and MRD algorithms, and the performance of algorithms is compared to that of SH. As previously mentioned, the decision went on implementing a reactive opportunistic strategy, which relies on intermediate nodes already having a known route. Although this option is expected to generate a unicast storm from opportunistic nodes, these can only transmit once the node connected to the CH finishes its transmission, hence generating minimal impact on the original algorithms. To limit any performance degradation, three additional rules are implemented. The first is a maximum transmission time for blind nodes to try and send their data, limiting overhead and the impact of opportunistic routes. Once the timeout occurs, nodes cannot use that specific relay and must find another alternative. The second strategy is a timer that, once an opportunistic node transmits its data, stops it from sending a new message for a period of time. The third is the removal of handshaking in opportunistic communications, to reduce overhead.

This section will focus on two main metrics: packet deliveryand mean distance between message origin and CH. While latency and collision are also important factors in WSNs, its increase is solely due to the added opportunistic strategy, and it is not considered essential to assess the performance of blind node routing.

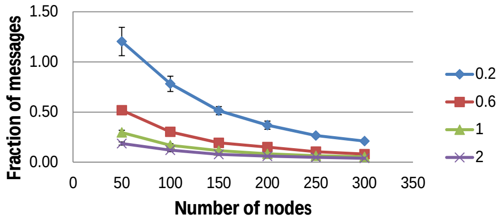
6.4.1 Greedy results

The addition of opportunistic routing in GR results in an increase of message delivery when PL exponent increases and wave height is low, as visible in figure 6.18. For PL>2, opportunistic GR improves the results of SH when the sea is flat and the cluster size is small. At points, the improvements are in excess of 20%. With $h > H$ there is a steep decrease in delivery, compared to SH. The combination of multi-hop and opportunistic strategies increase overhead when the number of blind spots increases.

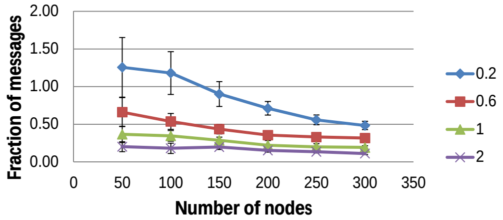
There is an overall increase in mean distance between origin and CH, as can be seen in figure 6.19. The distance improves significantly for higher PL exponents and lower wave height, reaching over 50% improvements under some conditions. With higher waves, CH advertisements do not reach all nodes within theoretical range. Therefore, some of the nodes at closer distance to the CH also become opportunistic to overcome the obstructed direct line of sight.



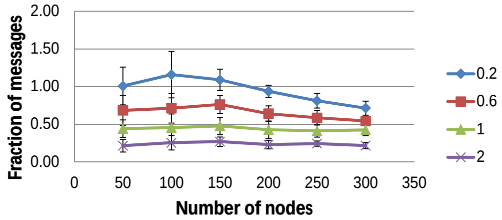
(a) PL=2



(b) PL=3

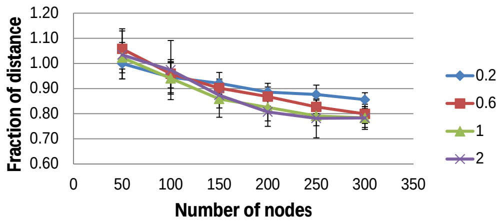


(c) PL=4

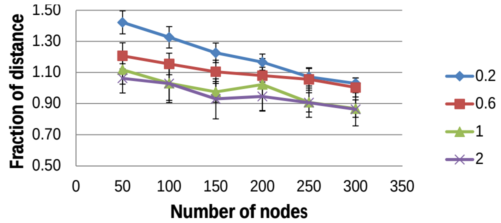


(d) PL=5

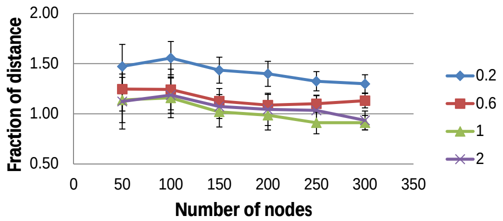
FIGURE 6.18: Packet delivery for GR opportunistic routing as a fraction of SH.



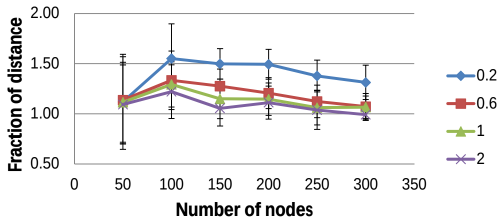
(a) PL=2



(b) PL=3



(c) PL=4



(d) PL=5

FIGURE 6.19: Mean distance between origin and CH for each received message as a fraction of SH.

6.4.2 Two-hop results

The results achieved with MRD are consistently better than those of SRD with lower PL exponents, and similar when PL is 4 and 5. As such, only MRD results will be analysed in this section. The two-hop scheme already provided delivery rates closer to those of SH for clear weather and smaller network sizes. With the introduction of opportunistic routing, the results get closer to the theoretical maximum for different weather conditions, as visible in the charts of figure 6.20. The delivery rate (when compared with SH) keeps closer to the maximum in smaller clusters. For larger network sizes, the delivery rate decreases mainly due to network congestion caused by bandwidth limitations.

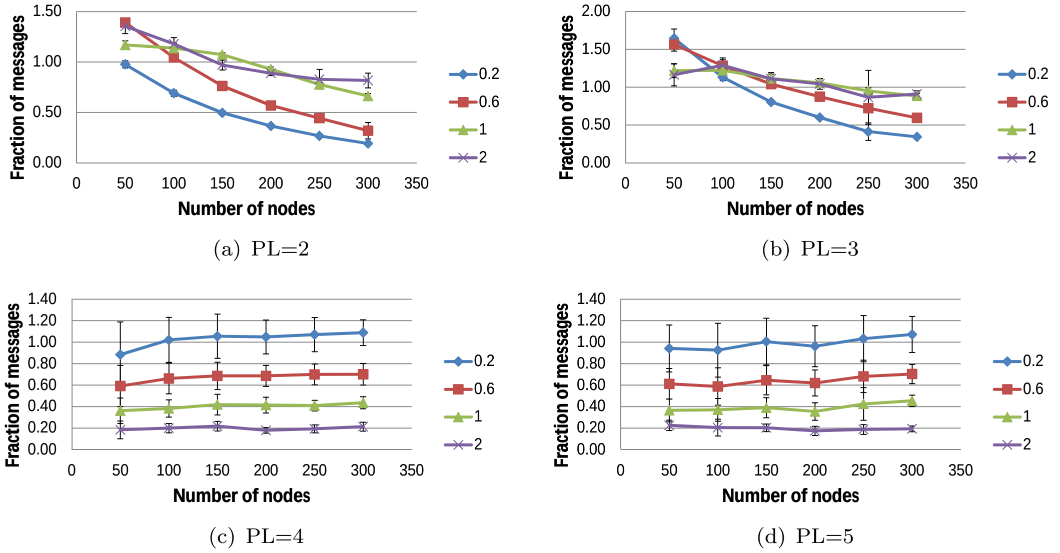


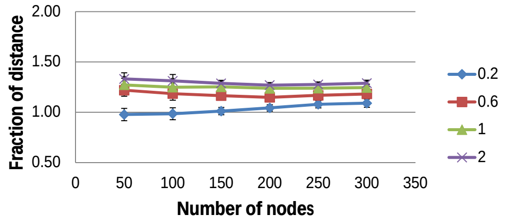
FIGURE 6.20: Packet delivery for MRD with opportunistic routing as a fraction of SH.

As with GR, the mean distance to the CH also improved over both standard MRD and SH, as shown in the charts of figure 6.21. The mean distance is consistently higher, and in some cases the improvement is greater than 50% compared to SH, and greater than 40% when compared to MRD without blind nodes. With lower PL, the results are consistently higher, except for the ideal case of PL $= 2$, $H = 0.2$m, as it is coincident with the near-optimal delivery. With higher PL, the improvements in distance are mainly noticeable with larger network sizes — these provide additional alternatives for opportunistic nodes to send their data.

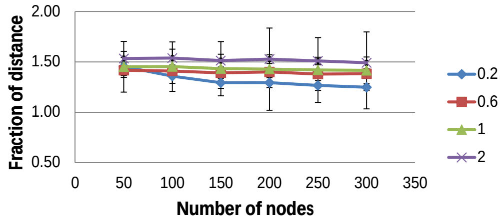
6.4.3 Discussion

Using opportunistic routing gives blind nodes another alternative to send their data to the CH. The implemented solution is based on a reactive strategy, where blind nodes use any transmitting node to relay their packets. This is based on the assumption that if a node is transmitting data, it is because it has found a route towards the CH. Nevertheless, there are two other sources of interference: other blind nodes and reduced transmission time. The first does not allow a node to know all its neighbours, therefore it will not know if its message is colliding. To save time, the handshake process was skipped when using an opportunistic route.

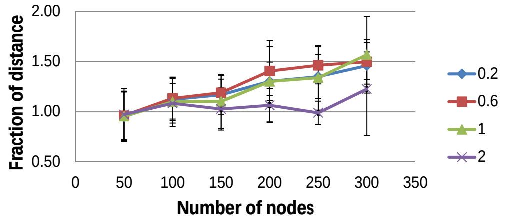
The overall packet delivery and mean distance to the CH for GR is improved in small networks and if PL > 2. At times, the delivery rate is over 20% higher than that of



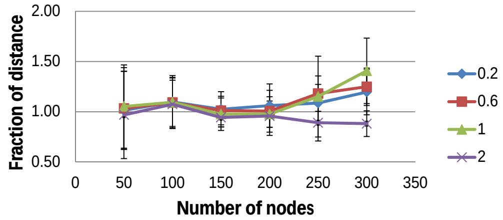
(a) PL=2



(b) PL=3



(c) PL=4



(d) PL=5

FIGURE 6.21: Mean distance between origin and CH with MRD routing as a fraction of SH.

SH. The mean distance is also higher for some of the simulation parameters, managing improvements higher than 50%.

Message delivery with MRD improved, when compared with SH. For smaller networks, it scored close to the theoretical maximum. Furthermore, the distance between origin and CH also improved, showing that opportunistic routing combined with two-hop routing is a better alternative for some cases. As with GR, this improvement occurs for smaller networks. Despite the reduced number of nodes within direct line of sight when $H > 0.6m$, the number of blind nodes competing for a known route increased.

6.5 Environment engine results

From the above results, it is possible to conclude that each algorithm provides distinctive scores for each set of simulation parameters. Yet, none of them is the ideal solution for the complete range of inputs tested. The environment engine aims at combining the results achieved, creating a metric that defines the best option for a given set of environmental conditions. Furthermore, as it can use both internal parameters and external data to manage these rules, a feedback loop is formed for the network adjustments. The outcome is a variable system that improves delivery and range to any set of inputs and interfering factors.

The results above were achieved for clearly defined network parameters. Although these represent generic ranges, the values inbetween those (e.g. PL =2.5) can be geometrically estimated and the environment manager decides upon that. The values beyond the

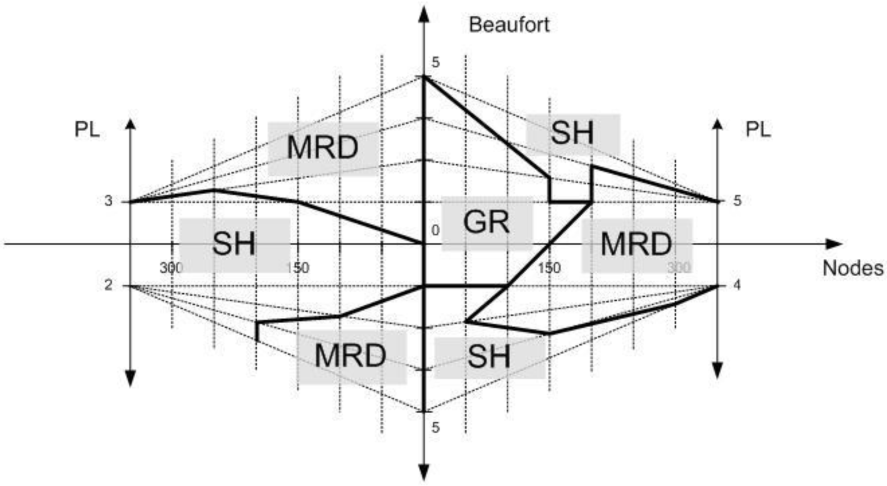


FIGURE 6.22: Geometric representation of routing decision.

simulated parameters (e.g. PL < 2 or PL> 5) will keep the same algorithm selection from the closest known set of parameters.

6.5.1 Routing decision

Equation 5.10 is used for PL=2 and PL=3. The scores are close, therefore this option provides a better relative score between algorithms. A wf of 1.5 emphasises the importance of packet delivery. Range has lower relevance as the deciding factor for these PL values since it its variation is mainly due to node's distribution.

Table 5.2 is used when PL=4 and PL=5. The values are too distant to consider using ratios. A $wf = 1$ is used, since it was considered that both packet delivery and range have the same importance in the choice of a successful solution with this set of parameters. Unlike for lower values of PL, the different algorithms may increase network range when compared with SH, especially in the case of opportunistic routing.

Not all the scores use the best solution: there is a compromise where the second best option can still be used for the sake of simplicity and consistency. Routing adaptation has advantages, yet frequent strategy changes may not be received and acknowledged by all nodes in range. The final decision is shown in figure 6.22, where the two main axes represent network size (in number of nodes) and wave height (the Beaufort number is used in correspondence). Path loss is divided into two axes for visibility purposes, where values from 2 to 5 are represented in four different axes. The thick lines contour the algorithm's range, representing the region of parameters where the algorithm provided the best results between those tested in the simulation. Multi-hop algorithms use opportunistic routing, as it provides higher delivery rate and greater mean distance between origin and CH than the non-opportunistic counterparts.

6.6 Discussion

The environment-aware engine allows the combination of more than one protocol into a WSN. In the current implementation, the CH chooses the best routing strategy for any given set of conditions, based on previous simulation results. As such, the network does not rely anymore on one single solution to provide the best output. Instead, it can modify its operation dynamically according to the set of inputs.

The current approach and scores are based on the algorithms and protocols presented in this thesis, as well as two generic alternatives. Other protocols were not considered as they needed to be adapted to the requirements of the deployment scenario, simulated and compared with the current implementations. Nevertheless, the results presented in this chapter show that it is important to understand the deployment and its main parameters before deciding which ones should be used and what should be their relative impact. By acknowledging these influences, it is then possible to modify the network behaviour accordingly, so that it always achieves the best performance.

6.7 General discussion

While designing and building a cross-layer routing algorithm, it was found that the simulation required a more detailed set of parameters and assumptions than those previously used while testing independent layers. In addition, the algorithms also required further decisions regarding their development and integration:

- The results were based on channel listening with multiple retries. As discussed in chapter 3, this solution can cause a latency increase towards the end of the period. To reduce the impact of unlimited retries and delays, nodes reset their buffers once they receive a new advertisement from the CH.
- Transmission period was kept constant to evaluate the implications of overhead in a large-scale, contention-based, reactive network. Packet delivery would increase in two-hop and multi-hop communication, should the advertised transmission period increase, as previously argued. Nevertheless, it would need to increase in a multiple of the network size (or exponential in the case of greedy algorithms) to maintain a constant delivery rate.
- Reactive routing is more suited to reduce overhead, especially considering the constant need to update paths in a dynamic network. Perhaps a proactive approach would be better suited when the weather conditions are close to optimal. Nevertheless, in such cases, SH proves to be a robust and reliable solution.

- MRD used all three alternatives to route messages from peripheral nodes, as opposed to a single alternative used in chapter 4. This is a trade-off between redundancy (thus increased packet delivery) and bandwidth usage to improve message delivery.

This work avoids route loss due to random obstacles through the use of reactive routing. This makes the algorithms self-healing and fault-tolerant towards random obstacles. The same principle is used in AODV [96] to reduce the risk of packet loss in intermediate nodes when these suddenly disappear. During the development, it was considered that proactive routing would impose a high increase in bandwidth usage, yet it would be relevant to discuss and test this in future work.

The proposed two-hop solutions are in some aspects similar to the LOCI algorithm [173]. With LOCI, the cluster is divided in two regions, the first is formed by nodes within direct range R of the CH, while the second is formed by nodes within $2R$ away. With SRD and MRD, all nodes must be within range of the CH, and the second hop is determined with R smaller than the maximum transmission range under optimal conditions. Furthermore, LOCI also repeats advertisements periodically, making it fault-tolerant. Yet, unlike LOCI, the CH is pre-determined and resource-rich, and nodes outside any CH range become opportunistic.

The algorithm adaptation implementation uses a fixed transmission power, independently of distance between nodes. This solution was also proposed in GEAR [113], where besides fixed transmitting power, the algorithm provides energy and geographic awareness. Also, as in GEAR, the proposed implementation does not use any routing or location database, and the nodes are in fixed locations. Unlike the algorithms presented in this thesis, and since GEAR uses fixed location, route update is random. This, combined with multi-hop and unawareness of full route cost, does not guarantee the minimum cost route from origin to destination. The two-hop strategies selected routes based on overall weight from origin to destination.

As the receivers were left operating continuously to minimise latency, the differences in energy consumption between nodes were minimal, thus remaining energy was left out of the route weight estimation. Energy saving can be added in future work through the implementation different MAC algorithms specifically designed to cope with sleep states, such as S-MAC.

Another important aspect that was considered during the design stage was scalability. Clustering is seen as the most scalable protocol [103], yet it is dependent on cluster size and intra-cluster communication. As claimed by Bjornemo et al. [155], multi-hop routing has fewer advantages than single-hop, particularly if origin and destination are within line of sight. The results showed that Greedy routing, when compared with single-hop, is advantageous under a limited set of conditions, such as small cluster size and when waves are higher than the antenna, causing obstruction.

In a network where all nodes are within range of a CH, the advantage of using multi-hop comes from the avoidance of random interferences. With Greedy, when a node decides to transmit, it requests the closest node towards the CH. Only nodes receiving the advertisement while being closer the CH can reply. This increases the chances of packet relay due to communication symmetry. Nevertheless, packet loss and overhead increases exponentially with the number of hops, despite the improved SINR due to short-range transmissions. This is more noticeable in large networks, where the number of transmissions limits packet reception, especially from peripheral nodes. Further investigation could analyse the ideal number of hops under different set of conditions. This alternative, combined with the switching between proactive and reactive, can trade between packet delivery, network coverage, bandwidth usage and latency.

The set of parameters measured in this chapter was different from those of chapter 4. As the network is expected to run for a few weeks (as described by the application scenario), lifetime is not a primary issue. Despite that, energy savings should be considered for future work. On the other hand, the combination between delivery rate and mean distance between origin and CH are essential to characterise the performance of algorithms.

When the weather is clear and there are no waves interfering, single-hop performs better than any other alternative. Packet delivery is close to the theoretical maximum and nodes can save energy through sleep states and low duty cycles. Single-hop also shows better results when the network size increases and more nodes become within range, mainly due to the smaller number of packets generated, when compared to multi-hop strategies. Therefore, network size is the first aspect to influence protocol's behaviour: smaller networks can cope with more complex protocols and benefit from their use, since the overhead they generate does not compromise a correct operation; however, as the network size grows, complex protocols slowly become irresponsive, while simpler solutions become more attractive. On the other hand, as nodes lose connectivity due to weather, multi-hop protocols become more suitable than single-hop.

By allowing blind nodes to discover opportunistic routes, the delivery rate and mean distance between origin and CH increase. Still, as these transmissions only start once the original packet was sent, the correct reception by the next hop (or CH) is guaranteed. The blind node strategy was based on a reactive approach without handshaking between nodes, despite potential collision and packet loss. This decision was taken for two reasons: (1) the relay node will have a known route to the CH; and (2) the influence of opportunistic routing in nodes within line-of-sight of a CH is minimised.

Developing an algorithm is always limited to a particular application or set of conditions. Understanding those conditions and their operating range in terms of network size, displacement and obstacles is important to the design of application-specific WSNs. The results shown in this chapter lead to the conclusion that there is no single solution to a deployment where conditions can change significantly and affect performance. Adding the possibility of changing the protocols locally and during network operation makes WSNs adapt their behaviour to both predictable and unforeseen conditions. As described in the literature and argued in this thesis, each routing protocol is designed for a specific set-up range and does not perform optimally on a broader set of conditions and parameters. Both network set-up and environmental issues affect the network performance to the extent of making it unusable. Although a single protocol solution can minimise this effect overall, it does not represent an optimal solution for every condition. As such, changing the protocol parameters — or eventually changing the whole protocol — is an approach to WSN design that results in using the best options at all times.

The decision process in the environment engine was based in two rules, both relying on information about packet delivery and message origin mean distance. While energy usage and latency are also important factors to consider, they become secondary when a high packet delivery (above 80% of generated packets) is not achievable. In such conditions, the primary focus was to guarantee that messages were delivered and the distance between origin and CH increased. GR and MRD outperformed SH by increasing the mean distance while maintaining a similar packet delivery. Latency was not considered (SH will always have the shortest delivery delay) and energy usage was left out intentionally, since the multi-hop algorithms kept nodes continuously awake.

The weather engine rules adopted in this work were straightforward. Further inputs from different sensors lead to additional fine graining and optimisation. The use of clustered networks allowed the centralisation of protocol selection rules in the CH. One alternative to consider in future research is the benefit of distributing the decision process through nodes. This option must consider a general failsafe rule and the implications of local decisions in the global cluster performance context.

The environment engine represents an important advance in understanding not only the limitations of the presented solutions, but also the general limitations of WSNs. Implementing different alternatives and clearly defining the decision rules allows the network to adapt to external factors, minimising their impact on node's communication. By doing so, the environment engine becomes the corollary of the influences of weather in network's behaviour and performance presented in this thesis.

6.8 Summary

In this chapter, the simulator developed was tested with different algorithms and under different sets of parameters. Maintaining the maritime monitoring scenario, the parameters and assumptions were evaluated according to the conditions expected to be found in an offshore network deployment. The results show that weather influences significantly the network performance, and that although one algorithm may work well under one set of environmental conditions, that is not necessarily the case for the full range of parameters.

Single-hop routing performance is nearly optimal with clear weather, yet it leaves margin for improvements when the weather becomes harsher. Packet delivery is the most important measure to estimate the network performance, although other parameters are needed to understand where the algorithms show deficiencies. By using mean distance between origin and CH, as well as collision rate estimation and latency, it was possible to identify under which conditions and solutions could be alternatives to SH.

The introduction of opportunistic routing showed improvements over non-opportunistic multi-hop strategies. Mean distance between origin and CH and packet delivery were improved, achieving better scores than the versions without it. Nevertheless, this strategy was not always advantageous, as larger networks can cause increased collisions and packet loss, particularly with Greedy. Therefore, a careful decision of which algorithm to use must be made, given the set of expected environmental conditions on the deployment area.

The combination of different parameters with the ability to change algorithms dynamically led to the introduction of the environment-aware engine. Its objective is to use each routing algorithm when it achieves the best results. By using a feedback mechanism, the engine can measure the implications of each modification on the network performance and, if necessary, run further adjustments.

Chapter 7

Conclusions

7.1 Summary

Wireless Sensor Networks allow sensing and monitoring in novel environments and contexts. To achieve this, WSNs must cope with the constraints found in the different locations. Hardware is another limitation of the concept: it relies on trade-offs to achieve the best compromise between cost, sensing, processing, communication and energy. To achieve the best results, application-aware development is fundamental. The application scenario is therefore essential to WSN development. It defines the characteristics, limitations and obstacles that the network will encounter when deployed. The combination of this set of challenges is very often unique to each case and requires the network development stage to take it into consideration so that the best solution can be found and implemented.

This thesis addresses solutions that allows a WSN to work under variable environmental conditions. In the scenario detailed in chapter 1, weather and network topology can vary during the monitoring operation, demanding specific design strategies to comply with the challenges. The objective was to develop network algorithms for MAC and Routing layers, integrate them into a custom-built simulator and assess their performance. The results led to the development of an adaptive communication model that adjusts the network behaviour according to ever-changing environmental conditions.

7.1.1 Medium Access Control

Medium access control strategies become increasingly more relevant as the network grows in size. The wireless bandwidth is limited, therefore the success of the network depends on MAC's performance. Moreover, MAC is also closely related to energy usage: to save energy, simpler protocols without any channel listening or negotiation provide the extreme case of energy savings, at the cost of lower packet delivery rate. More complex solutions, on the other hand, trade energy for higher packet delivery. It was shown that the trade-off is linear and it depends on a ratio between number of nodes, transmission period, frequency and bandwidth. Ultimately, the most efficient techniques are needed to improve message delivery and bandwidth usage while keeping energy consumption low.

Using extended range transmitters was one of the decisions affecting mainly the MAC layer. The number of nodes within transmission range increases exponentially with a linear increase in transmission range, for a given uniform distribution. Nodes compete for the same limited channel, increasing the probability of collision, hence contention and retransmission. On the other hand, long-range communication results in smaller number of clusters and lower complexity in upper layers.

In chapter 3, it was shown that even with protocols that require less control messages it is still possible to keep a very high message delivery (above 85%) while reducing the overhead to a minimum. The biggest concern was related to hidden nodes and the amount of collisions that they can cause. Listening to the channel before transmitting is a simple practice that reduces the probability of collision between nodes without affecting bandwidth usage. The energy cost of such procedure is also relatively small when compared with the overall improvement in message delivery. As such, it represents a solid alternative to more complex mechanisms under the described scenario.

7.1.2 Two-hop routing

The comparison between single-hop and multi-hop techniques has given an insight into how the energy is used not only by one node, but by the network as a whole. Nodes must cooperate between them to achieve the best results while prolonging the network operation. The results in this thesis showed that, under certain conditions, two-hop routing can extend the network lifetime while keeping a low latency and collision rate.

Two-hop schemes are the simplest multi-hop strategies and, as shown in chapter 4, they can guarantee an increase in network lifetime. When compared with single-hop and Greedy, two-hop balance energy depletion between long and short range transmissions at the cost of small yet predictable increase in latency. Three different approaches to two-hop routing algorithms were implemented. As demonstrated, even simple decisions and small modifications in routing strategies can significantly affect the overall performance. Furthermore, the results led to the conclusion that, to achieve the best results, nodes need to be aware of not only their status but also of the status of their neighbours. This way, self-interest is minimised and global awareness improved. A combination between energy and distance provided a metric that improved network lifetime by over 50%

when compared with single-hop, approaching the ideal solution where all nodes become depleted at the same instant.

7.1.3 Environment-aware simulation and results

Building a network simulator demands an understanding of node behaviour, network interactions and external factors that can influence its operation. To that extent, the use of realistic models for both communication and weather is fundamental to achieve trustworthy results in an environmental-aware simulation. This leads to the design and tuning of communication algorithms and protocols to better fit the proposed scenario.

The simulation development described in chapter 5 was centred on realistic network environments and on the dynamic behaviour of variable size networks. The network was partitioned into clusters, thus allowing logical and physical division between regions. This also allows the simulation of one single cluster, whose results are replicated across the network. Despite the realistic approach, assumptions and simplifications were required where the full extent of alternatives was only possible under real deployment conditions. The routing algorithms used in the simulator were based on the proposals presented in chapters 3 and 4. These were modified due to cross-layer requirements to include both application and physical layers. The algorithms were tested with different parameters to simulate weather and network characteristics. The results in chapter 6 have shown that each algorithm reacts differently to modifications in parameters. Furthermore, there are different scores for each set of parameters: one algorithm can score better in one metric, yet prove worse in the others. This proved that one algorithm can be the best solution to a particular problem or set of rules but only after considering which metrics and scores are important to the specific deployment, and if their combination still provides the highest value amongst the alternatives.

In a direct comparison, each algorithm shows different advantages and drawbacks. Most importantly, their performance depends on the network size and displacement, as well as weather conditions. Considering the most important metrics — packet delivery and mean distance between origin and CH —, SH approaches the ideal message delivery rate when the weather is clear and sea is flat. Greedy is best for small size networks and harsh weather, while MRD outperforms SH and Greedy either when the network is small and weather is clear, or when the network is larger and attenuation is high.

7.1.4 Environment-aware engine

Considering the application scenario of this thesis, weather changes (hence parameter changes) can be frequent. To cope with this, chapter 5 introduced the environment-aware engine. The engine is parallel to the network operations and its purpose is to modify and adapt the routing algorithms according to sensed values and communication-derived statistics. The use of a feedback loop mechanism also helps to further improve the network performance by using a metric based on external and internal metrics, and their influence on the network behaviour upon any modification.

The engine uses two different rules according to the estimated value of path loss. Packet delivery rate and mean distance between origin and the CH are used for that purpose. The difference is in the figure of merit attributed by each rule. This approach emphasises the need to understand the particularities of each deployment and application to adapt the network accordingly. Moreover, by having full awareness of the influence of both network behaviour and weather conditions, it is possible to continually monitor and modify the network protocols and improve the results. The engine is the evidence that an adaptive sensor network provides the best solution in dynamic deployment environments.

The engine was developed for maritime monitoring, yet it can be expanded and adapted to suit other applications with a variable set of conditions and where more than one protocol can be used to improve performance.

7.2 Contributions

This thesis successfully contributed to the understanding of WSNs in the areas outlined in chapter 1:

Variable size and topology networks. Dividing the network into clusters provided the basic procedure to reduce collisions when the network size varies. Intra-cluster communication has a fundamental role in the network performance. Making a hardware selection based on both envisioned deployment strategy and expected network size worked as the basis for the solution found.

Medium access mechanisms. Chapter 3 analysed collision and hidden nodes from a theoretical perspective, proved through simulation. It was shown that the ratio between transmission period and number of nodes is an important measure to estimate packet delivery in contention-based medium access, minimising hidden and exposed terminal problems, and consequently improving energy efficiency.

Energy distribution. As shown in chapter 4, multi-hop can improve energy usage under specific circumstances, when compared to single-hop. In addition, it was shown that the location of nodes is also of extreme importance when balancing energy between origin and intermediate nodes. Furthermore, nodes must have a global knowledge of the neighbour's status to avoid greedy and unbalanced battery depletion across the network. This work shows that simple two-hop solutions can improve energy consumption with minimal impact on metrics.

Environment-aware communication. The combination between hardware, firmware and environment-aware decisions is an essential aspect of WSN development. The environment engine was designed to adapt network algorithms according to weather changes, adjusting performance under variable conditions. The engine is a framework that works in parallel with the network stack. It combines sensing and network performance data into a metric used to improve communication. Therefore it can work with different environments, sets of rules and algorithms.

When taken together, this thesis made a significant contribution towards the understanding of the interactions and implications between WSN development and deployment environment. Still, much remains to be investigated.

7.3 Future work

The research conducted for this thesis has successfully met the research objectives and aims proposed in section 1.3. Nonetheless, research in routing and networking is constantly evolving and novel algorithms and models can be added to expand this research. This section outlines the areas that can be addressed by future work.

7.3.1 Two-hop routing and cross-layer development

To improve the routing algorithms presented in this thesis, further research is needed on how to dynamically adjust the two-hop range distribution. As it was found, the static rule has limitations mainly due to the fixed relay range. Using a dynamic relaying area that depends on communication and environmental factors will improve the decisions of whether a node should act as intermediate or not. MRD can also be modified to adapt the number of relays according to weather conditions and network size. When the network grows, more nodes will be within communication range, hence the number of usable relays. On the other hand, as weather gets harsher, fewer nodes are within range, thus the number of relays is smaller. Research can be conducted to balance communication range, number of nodes in the vicinity and variability of weather with the delivery rate and bandwidth usage.

Reactive opportunistic routing was described and used in this thesis. The proactive approach is expected to generate greater overhead, particularly in larger andhighly mobile networks. Nevertheless, it can still be an alternative for particular weather conditions, should it prove to outperform the reactive solution. Another aspect that can lead to further research is the use of asymmetric transmission ranges. This can be either through fitting the sink/CH with a transceiver with higher transmitting power than that of sensing nodes, or by fitting two transceiver with different gains in nodes. Each node would select the most appropriate option for each case, either by appointment of the CH or through internal algorithm (and environment engine) decisions.

7.3.2 General-purpose adaptive network routing

The adaptive engine concept was shown and proven to work with simple decision rules. Future work can include a distributed fuzzy logic management scheme to decide routing in nodes, or the use of Artificial Neural Networks to control a larger number of variables, creating rankings and weigh inputs to optimise network performance. Ultimately, the wireless sensors can use any of the protocols and decision rules that lead to a general-purpose, self-healing and self-optimising WSN. Another option to adapt network algorithms' external changes is through the use of game theory to assist with local strategy decision, particularly in the case of implementing the engine in sensing nodes. This would help to solve regional issues, whereas the CH only has a centralised point of view of the network.

Aiding protocol adaptation through minor modifications, wireless communication can be used to re-program the network where the current parameter adjustment and routing scheme selection is insufficient. When the network is controlled by a sink/CH, this device becomes the ideal candidate to broadcast the modifications required. The performance changes are assessed by the environment engine, leading to further fine-tuning when needed.

7.3.3 WSN deployment at sea

The simulator was developed using realistic channel models. However, the parameters were solely based on expected path loss exponent and wave height values. By deploying a WSN at sea, it is possible to understand the differences between the simulated and the real values, thus fine-tuning the models to replicate the exact conditions found. Another important aspect that can only be assessed through deployment is the influence of ocean wave length into long distance transmissions. The literature does not relate wave height with length, and its full impact must be measured on-site and with different weather conditions.

Bibliography

[1] I Akyildiz, W Su, Y Sankarasubramaniam, and E Cayirci. Wireless sensor networks: a survey. *Computer Networks*, 38:393–422, 2002.

[2] David Culler, Deborah Estrin, and Mani Srivastava. Guest editors' introduction: Overview of sensor networks. *Computer*, 37(8):41–49, 2004.

[3] Li Zheng. Zigbee wireless sensor network in industrial applications. In *SICE-ICASE, 2006. International Joint Conference*, pages 1067–1070, 2006.

[4] Geoff Werner-Allen, Konrad Lorincz, Mario Ruiz, Omar Marcillo, Jeff Johnson, Jonathan Lees, and Matt Welsh. Deploying a wireless sensor network on an active volcano. *IEEE Internet Computing, Special Issue on Data-Driven Applications in Sensor Networks*, March/April 2006.

[5] K Martinez, J Hart, and R Ong. Environmental sensor networks. *IEEE Computer*, 37(8):50–56, 2004.

[6] Chris R. Baker, Kenneth Armijo, Simon Belka, Merwan Benhabib, Vikas Bhargava, Nathan Burkhart, Artin Der Minassians, Gunes Dervisoglu, Lilia Gutnik, M. Brent Haick, Christine Ho, Mike Koplow, Jennifer Mangold, Stefanie Robinson, Matt Rosa, Miclas Schwartz, Christo Sims, Hanns Stoffregen, Andrew Waterbury, Eli S. Leland, Trevor Pering, and Paul K. Wright. Wireless sensor networks for home health care. *Advanced Information Networking and Applications Workshops, 2007, AINAW '07. 21st International Conference on*, 2:832–837, May 2007.

[7] Deborah Estrin, Ramesh Govindan, John S Heidemannand, and Satish Kumar. Next century challenges: Scalable coordination in sensor networks. In *Mobile Computing and Networking*, pages 263–270, 1999.

[8] G J Pottie and W J Kaiser. Wireless integrated network sensors. *Communications of the ACM*, 43(5):51–58, 2000.

[9] Athanasios Stathopoulos. *Exploiting heterogeneity for routing in wireless sensor networks.* PhD thesis, 2006.

[10] A.D. Siuli Roy and S. Bandyopadhyay. Agro-sense: Precision agriculture using sensor-based wireless mesh networks. In *Innovations in NGN: Future Network and*

Services, 2008. K-INGN 2008. First ITU-T Kaleidoscope Academic Conference, pages 383–388, May 2008.

[11] Alan Mainwaring, David Culler, Joseph Polastre, Robert Szewczyk, and John Anderson. Wireless sensor networks for habitat monitoring. In *WSNA '02: Proceedings of the 1st ACM international workshop on Wireless Sensor Networks and applications*, pages 88–97. ACM Press, 2002.

[12] Sasikanth Avancha, Jeffrey L Undercoffer, Anupam Joshi, and John Pinkston. *Wireless Sensor Networks*, chapter Security for Sensor Networks, pages 253–275. Kluwer Academic Publishers, 2004.

[13] S. Yamagishi, K. Hitomi, H. Yamanouchi, Y. Yamaguchi, and T. Shibata. Development and test of a compact lidar for detection of oil spills in water. In R. J. Frouin, H. Kawamura, & M. Kishino, editor, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, volume 4154, pages 136–144, January 2001.

[14] Iwona Maciejewska. Real time oil spill detection and tracking based on air-born and satellite remote sensing technologies. Technical report, SPREEX – SPill REsponse EXperience, www.spreex.net [online], 2007.

[15] Nils Robbe and Theo Hengstermann. Latest trends in airborne pollution surveillance. *Sea Technology*, pages 41–44, October 2007.

[16] Cobham Tracking & Locating Ltd. [Online]. *RF-700C2 - Combo Oil Spill Tracker.* www.seimac.com/, 2008.

[17] EnviroWatch Global Enviro Network, Inc. [Online]. *Genesis Alert System.* http://www.genalert.com/, 2002.

[18] Met Office [Online]. *The Beaufort scale.* `http://www.metoffice.gov.uk/education/secondary/students/beaufort.html`, 2008.

[19] Open University. *Ocean Circulation - Second Edition.* Butterworth-Heinemann, 2001.

[20] Stephen Pond and George L Pickard. *Introductory Dynamical Oceanography*, volume 2. Pergamon Press, Oxford, 1983.

[21] M Britton and L Sacks. The SECOAS Project: Development of a Self-Organising, Wireless Sensor Network for Environmental Monitoring. In *Second International Workshop on Sensor and Actor Network Protocols and Applications (SANPA 2004)*, August 2004.

[22] Jane Tateson, Christopher Roadknight, Antonio Gonzalez, Taimur Khan, Steve Fitz, Ian Henning, Nathan Boyd, Chris Vincent, and Ian Marshall. Real world

issues in deploying a wireless sensor network for oceanography. In *Workshop on Real-World Wireless Sensor Networks (REALWSN'05)*, 2005.

[23] S Nittel, N Trigoni, and N Pettigrew. Data management in mobile ad-hoc ocean sensor networks. In *NSF-sponsored Workshop on Mobile Adhoc Sensor Networks (position paper)*, 2007.

[24] Rick Lumpkin and Mayra Pazos. *Lagrangian Analysis and Prediction of Coastal and Ocean Dynamics (LAPCOD)*, chapter 2, pages 39–67. Cambridge University Press, 2006.

[25] Sutharshan Rajasegarar, Jayavardhana Gubbi, Olga Bondarenko, Stuart Kininmonth, Slaven Marusic, Scott Bainbridge, Ian Atkinson, and Marimuthu Palaniswami. Sensor Network Implementation Challenges in The Great Barrier Reef Marine Environment. In *Proceedings ICT Mobile Summit (ICT Summit 2008)*, Stockholm, Sweden, Jun 2008.

[26] Mingxing Jiang, Zhongwen Guo, Feng Hong, Yutao Ma, and Hanjiang Luo. Oceansense: A practical wireless sensor network on the surface of the sea. In *Pervasive Computing and Communications, 2009. PerCom 2009. IEEE International Conference on*, pages 1–5, 2009.

[27] Umberto M. Cella, Nicholas Shuley, and Ron Johnstone. Wireless sensor networks in coastal marine environments: a study case outcome. In *WUWNet '09: Proceedings of the Fourth ACM International Workshop on UnderWater Networks*, pages 1–8. ACM, 2009.

[28] Council European Parliament. Directive 2005/35/EC of the European Parliament and of the Council of 7 September 2005 on ship-source pollution and on the introduction of penalties for infringements. *Official Journal of the European Union*, L 225(2005/35/EC):11–21, 2005.

[29] European Council. Council Framework Decision 2005/667/JHA of 12 July 2005 to strengthen the criminal-law framework for the enforcement of the law against ship-source pollution. *Official Journal of the European Union*, L 255(2005/667/JHA): 11–21, 2005.

[30] European Union [Online]. Maritime safety: Ship-source pollution and criminal penalties. `http://europa.eu/legislation_summaries/environment/water_protection_management/index_en.htm`.

[31] European Maritime Safety Agency (EMSA) [Online]. `http://www.emsa.europa.eu/`.

[32] Luc Hogie, Pascal Bouvry, and Frédéric Guinand. An overview of manets simulation. *Electronic Notes in Theoretical Computer Science*, 150(1):81–101, 2006.

[33] Stephen P. Murray. Turbulent diffusion of oil in the ocean. *Limnology and Oceanography*, 17(5):651–660, 1972.

[34] J M Kahn, R H Katz, and K S J. Pister. Next century challenges: mobile networking for smart dust. In *MobiCom '99: Proceedings of the 5th annual ACM/IEEE international conference on Mobile computing and networking*, pages 271–278. ACM Press, 1999.

[35] Mark Weiser. The computer for the 21st century. *SIGMOBILE Mobile Computing and Communications Review*, 3(3):3–11, July 1999.

[36] Qing Zhao, Lang Tong, and Yunxia Chen. Energy-aware data-centric mac for application-specific sensor networks. In *Proc. of IEEE Workshop on Statistical Signal Processing*, 2005.

[37] Hai N. Pham, Dimosthenis Pediaditakis, and Athanassios Boulis. From simulation to real deployments in wsn and back. In *World of Wireless, Mobile and Multimedia Networks, 2007. WoWMoM 2007. IEEE International Symposium on a*, pages 1–6, June 2007.

[38] Adrian Perrig, John Stankovic, and David Wagner. Security in wireless sensor networks. *Communications of the ACM*, 47(6):53–57, 2004.

[39] Bhaskaran Raman and Kameswari Chebrolu. Censor networks: a critique of "ensor networks" from a systems perspective. *SIGCOMM Computer Communication Review*, 38(3):75–78, 2008.

[40] G Giancola, L Blazevic, I Bucaille, L De Nardis, M-G Di Benedetto, Y Durand, G Froc, B M Cuezva, J-B Pierrot, P Pirinen, and N Rinaldi. UWB MAC and network solutions for low data rate with location and tracking applications. In *IEEE International Conference on Ultra-Wideband*, pages 758–763, 2005.

[41] Liang Zhaohui. High data rate ultra wideband system design for wireless sensor network. In *ICSNC '07: Proceedings of the Second International Conference on Systems and Networks Communications*, page 39. IEEE Computer Society, 2007.

[42] Yong Yao and Johannes Gehrke. The cougar approach to in-network query processing in sensor networks. *SIGMOD Rec.*, 31(3):9–18, 2002.

[43] J. Polastre, R. Szewczyk, and D. Culler. Telos: enabling ultra-low power wireless research. *Information Processing in Sensor Networks, 2005. IPSN 2005. Fourth International Symposium on*, pages 364–369, April 2005.

[44] G. Anastasi, A. Falchi, A. Passarella, M. Conti, and E. Gregori. Performance measurements of motes sensor networks. In *MSWiM '04: Proceedings of the 7th ACM international symposium on Modeling, analysis and simulation of wireless and mobile systems*, pages 174–181. ACM, 2004.

[45] Wei Ye and John Heidemann. Medium access control in wireless sensor networks. *Wireless sensor networks*, pages 73–91, 2004.

[46] Kurtis Kredo, II and Prasant Mohapatra. Medium access control in wireless sensor networks. *Comput. Netw.*, 51(4):961–994, 2007.

[47] Abtin Keshavarzian, Huang Lee, and Lakshmi Venkatraman. Wakeup scheduling in wireless sensor networks. In *MobiHoc '06: Proceedings of the 7th ACM international symposium on Mobile ad hoc networking and computing*, pages 322–333. ACM, 2006.

[48] N.M. Pletcher, S. Gambini, and J.M. Rabaey. A 2ghz 52w wake-up receiver with -72dbm sensitivity using uncertain-if architecture. *Solid-State Circuits Conference, 2008. ISSCC 2008. Digest of Technical Papers. IEEE International*, pages 524–633, Feb. 2008.

[49] Niannian Ding and Peter Xiaoping Liu. Data gathering communication in wireless sensor networks using ant colony optimization. In *Proceedings of the 2004 IEEE International Conference on Robotics and Biomimetics*, pages 822–827, 2004.

[50] Microchip Technology Inc. [Online]. *Microchip MRF24J40 datasheet.* www.microchip.com/wwwproducts/Devices.aspx?dDocName=en027752, 2008.

[51] Ember Corporation [Online]. *Ember EM250 System-on-Chip* . www.ember.com/products_zigbee_chips_e250.html, 2008.

[52] Chipcon AS [Online]. *Chipcon/Texas Instruments product guide.* www.ti.com, 2008.

[53] Freescale Semiconductor Inc. [Online]. *Freescale 802.15.4 Transceivers* . www.freescale.com, 2008.

[54] RFM Monolithics, Inc. [Online]. *RFM 802.15.4 network devices.* http://rfm.com/products/802154.shtml, 2008.

[55] Feng Xue and P. R. Kumar. On the θ-coverage and connectivity of large random networks. *IEEE/ACM Transactions on Networking*, 14(SI):2289–2299, 2006.

[56] Feng Xue and P. R. Kumar. The number of neighbors needed for connectivity of wireless networks. *Wirel. Netw.*, 10(2):169–181, 2004.

[57] Yu Chen and Eric Fleury. Latency of event reporting in duty-cycled wireless sensor networks. In *Mobile Ad-hoc and Sensor Networks*, pages 711–723, 2006.

[58] Antonio G. Ruzzelli, Richard Tynan, and G. M. P. O'Hare. An energy-efficient and low-latency routing protocol for wireless sensor networks. In *ICW '05: Proceedings of the 2005 Systems Communications*, pages 449–454. IEEE Computer Society, 2005.

[59] A J Goldsmith and S B Wicker. Design challenges for energy-constrained ad hoc wireless networks. *IEEE Wireless Communications*, 9(4):8–27, 2002.

[60] Y Zhang and L Cheng. Cross-layer optimization for sensor networks. In *New York Metro Area Networking Workshop 2003*, New York City, NY, U.S.A., 2003.

[61] IEEE 802.15.4 WPAN-LR Task Group. Standard for part 15.4: Wireless mac and phy specifications for low rate wpan. IEEE Computer Society, September 2006.

[62] ZigBee Alliance [Online]. Zigbee specification: Zigbee documentation 053474r17. www.zigbee.org, October 2007.

[63] ZigBee Alliance [Online]. Zigbee-pro stack profile: Zigbee documentation 074855r05. www.zigbee.org, January 2008.

[64] Internet LAB [online]. *6LoWPAN: IPv6-based Low-Power Wireless Personal Area Netowkrs*. www.6lowpan.net, 2007.

[65] G Montenegro and N Kushalnagar. RFC draft:transmission of ipv6 packets over ieee 802.15.4 networks, 2007.

[66] G. Montenegro, N. Kushalnagar, J. Hui, and D. Culler. Transmission of IPv6 Packets over IEEE 802.15.4 Networks. RFC 4944 (Proposed Standard), September 2007.

[67] Bluetootn SIG [ONLINE]. Bluetooth Low Ehergy Core Specification V4.0. `http://www.bluetooth.com/`, 2009.

[68] Holger Karl and Andreas Willig. *Protocols and Architectures for Wireless Sensor Networks*. Wiley-Interscience, 2007.

[69] Theodore Rappaport. *Wireless Communications: Principles and Practice*. Prentice Hall PTR, 2001.

[70] K.G. Langendoen. Medium access control in wireless sensor networks. In H. Wu and Y. Pan, editors, *Medium Access Control in Wireless Networks*, pages 535–560. Nova Science Publishers, Inc., may 2008.

[71] L. Kleinrock and F. Tobagi. Packet switching in radio channels: Part i–carrier sense multiple-access modes and their throughput-delay characteristics. *Communications, IEEE Transactions on [legacy, pre - 1988]*, 23(12):1400–1416, Dec 1975.

[72] Norman Abramson. The aloha system: another alternative for computer communications. In *AFIPS '70 (Fall): Proceedings of the November 17–19, 1970, fall joint computer conference*, pages 281–285. ACM, 1970.

[73] J. Metzner. On improving utilization in aloha networks. *Communications, IEEE Transactions on*, 24(4):447–448, Apr 1976.

[74] Andrew Tanenbaum. *Computer Networks.* Prentice Hall Professional Technical Reference, 2002.

[75] Peng-Jung Wu and Chung-Nan Lee. On-demand connection- oriented multi-channel mac protocol for ad-hoc network. *Sensor and Ad Hoc Communications and Networks, 2006. SECON '06. 2006 3rd Annual IEEE Communications Society on*, 2:621–625, Sept. 2006.

[76] Wei Ye, J. Heidemann, and D. Estrin. An energy-efficient mac protocol for wireless sensor networks. *INFOCOM 2002. Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE*, 3:1567–1576, 2002.

[77] Joseph Polastre, Jason Hill, and David Culler. Versatile low power media access for wireless sensor networks. In *SenSys '04: Proceedings of the 2nd international conference on Embedded networked sensor systems*, pages 95–107. ACM, 2004.

[78] P Levis, S Madden, J Polastre, R Szewczyk, K Whitehouse, A Woo, D Gay, J Hill, M Welsh, E Brewer, and D Culler. *Ambient Intelligence*, chapter TinyOS: an operating system for sensor networks, pages 115–148. Springer Berlin Heidelberg, 2005.

[79] C.C. Enz, A. El-Hoiydi, J.-D. Decotignie, and V. Peiris. Wisenet: an ultralow-power wireless sensor network solution. *Computer*, 37(8):62–70, Aug. 2004.

[80] G. Lu, B. Krishnamachari, and C.S. Raghavendra. An adaptive energy-efficient and low-latency mac for data gathering in wireless sensor networks. *Parallel and Distributed Processing Symposium, 2004. Proceedings. 18th International*, pages 224–, April 2004.

[81] Venkatesh Rajendran, Katia Obraczka, and J. J. Garcia-Luna-Aceves. Energy-efficient collision-free medium access control for wireless sensor networks. In *SenSys '03: Proceedings of the 1st international conference on Embedded networked sensor systems*, pages 181–192. ACM, 2003.

[82] W R Heinzelman, A Chandrakasan, and H Balakrishnan. Energy-efficient communication protocol for wireless microsensor networks. In *Proceedings of the 33rd Annual Hawaii International Conference on System Sciences*, volume 2, 2000.

[83] Paolo Santi. *Topology control in wireless ad hoc and sensor networks.* John Wiley & Sons, September 2005.

[84] Jamal N Al-Karaki and Ahmed E Kamal. Routing techniques in wireless sensor networks: a survey. *IEEE Wireless Communications*, 11(16):6–28, Dec 2004.

[85] Qiangfeng Jiang and D Manivannan. Routing protocols for sensor networks. In *Consumer Communications and Networking Conference, 2004. CCNC 2004. First IEEE*, pages 93–98, 2004.

[86] Jerry Zhao and Ramesh Govindan. Understanding packet delivery performance in dense wireless sensor networks. In *SenSys '03: Proceedings of the 1st international conference on Embedded networked sensor systems*, pages 1–13. ACM Press, 2003.

[87] Feng Xia. Qos challenges and opportunities in wireless sensor/actuator networks. *Sensors*, 8:1099–1110, 2007.

[88] Sze-Yao Ni, Yu-Chee Tseng, Yuh-Shyan Chen, and Jang-Ping Sheu. The broadcast storm problem in a mobile ad hoc network. In *MobiCom '99: Proceedings of the 5th annual ACM/IEEE international conference on Mobile computing and networking*, pages 151–162. ACM Press, 1999.

[89] D. Ganesan, B. Krishnamachari, A. Woo, D. Culler, D. Estrin, and S. Wicker. An empirical study of epidemic algorithms in large scale multihop wireless networks, 2002. Submitted for publication, February 2002.

[90] D. Ganesan, B. Krishnamachari, A. Woo, D. Culler, D. Estrin, and S. Wicker. Complex behavior at scale: An experimental study of low-power wireless sensor networks. Technical report, UCLA Computer Science Department, 2002.

[91] Zygmunt J. Haas, Joseph Y. Halpern, and Li Li. Gossip-based ad hoc routing. *IEEE/ACM Trans. Netw.*, 14(3):479–491, 2006.

[92] Olivier Dousse, Petteri Mannersalo, and Patrick Thiran. Latency of wireless sensor networks with uncoordinated power saving mechanisms. In *MobiHoc '04: Proceedings of the 5th ACM international symposium on Mobile ad hoc networking and computing*, pages 109–120. ACM, 2004.

[93] David Braginsky and Deborah Estrin. Rumor routing algorthim for sensor networks. In *WSNA '02: Proceedings of the 1st ACM international workshop on Wireless sensor networks and applications*, pages 22–31. ACM Press, 2002.

[94] Chalermek Intanagonwiwat, Ramesh Govindan, and Deborah Estrin. Directed diffusion: a scalable and robust communication paradigm for sensor networks. In *Mobile Computing and Networking*, pages 56–67, 2000.

[95] Wendi Rabiner Heinzelman, Joanna Kulik, and Hari Balakrishnan. Adaptive protocols for information dissemination in wireless sensor networks. In *MobiCom '99: Proceedings of the 5th annual ACM/IEEE international conference on Mobile computing and networking*, pages 174–185. ACM Press, 1999.

[96] Charles E. Perkins and Elizabeth M. Royer. Ad-hoc on-demand distance vector routing. In *In Proceedings of the 2nd IEEE Workshop on Mobile Computing Systems and Applications*, pages 90–100, 1999.

[97] C. Perkins, E. Belding-Royer, and S. Das. Rfc 3561: Ad hoc on-demand distance vector (AODV) routing. Technical report, IETF Network Working Group, 2003.

[98] Charles E. Perkins and Pravin Bhagwat. Highly dynamic destination-sequenced distance-vector routing (DSDV) for mobile computers. *SIGCOMM Comput. Commun. Rev.*, 24(4):234–244, 1994.

[99] David B. Johnson, David A. Maltz, and Yih C. Hu. Rfc 4738: The dynamic source routing protocol for mobile ad hoc networks (dsr). Technical report, IETF MANET Working Group, February 2007.

[100] Kemal Akkaya and Mohamed F. Younis. A survey on routing protocols for wireless sensor networks. *Ad Hoc Networks*, 3(3):325–349, 2005.

[101] M. Ding, X. Cheng, and G. Xue. Aggregation tree construction in sensor networks. *Vehicular Technology Conference, 2003. VTC 2003-Fall. 2003 IEEE 58th*, 4:2168–2172, 2003.

[102] Peng Ji, Chendong Wu, Yunzhou Zhang, and Zixi Jia. Research of balanced-alternative spanning tree for wireless sensor networks. *Wireless Communications, Networking and Mobile Computing, 2007. WiCom 2007. International Conference on*, pages 2547–2550, 2007.

[103] Ameer Ahmed Abbasi and Mohamed Younis. A survey on clustering algorithms for wireless sensor networks. *Comput. Commun.*, 30(14–15):2826–2841, 2007.

[104] S. Lindsey and C.S. Raghavendra. PEGASIS: Power-efficient gathering in sensor information systems. *Aerospace Conference Proceedings, 2002. IEEE*, 3:3–1125–3–1130, 2002.

[105] A. Manjeshwar and D.P. Agrawal. TEEN: a routing protocol for enhanced efficiency in wireless sensor networks. *Parallel and Distributed Processing Symposium., Proceedings 15th International*, pages 2009–2015, 2001.

[106] A. Manjeshwar and D.P. Agrawal. APTEEN: a hybrid protocol for efficient routing and comprehensive information retrieval in wireless sensor networks. *Parallel and Distributed Processing Symposium., Proceedings International, IPDPS 2002, Abstracts and CD-ROM*, pages 195–202, 2002.

[107] S. Nikoletseas, I. Chatzigiannakis, H. Euthimiou, A. Kinalis, A. Antoniou, and G. Mylonas. Energy efficient protocols for sensing multiple events in smart dust networks. *Simulation Symposium, 2004. Proceedings. 37th Annual*, pages 15–24, 2004.

[108] Benjie Chen, Kyle Jamieson, Hari Balakrishnan, and Robert Morris. Span: an energy-efficient coordination algorithm for topology maintenance in ad hoc wireless networks. *Wireless Networks*, 8(5):481–494, 2002.

[109] Ossama Younis, Marwan Krunz, and Srinivasan Ramasubramanian. Node clustering in wireless sensor networks: recent developments and deployment challenges. *IEEE Network*, 20(3):20–25, 2006.

[110] T. C. Karalar and J. M Rabaey. An rf tof based ranging implementation for sensor networks. In *2006 IEEE International Conference on Communications*, pages 3347–3352, 2006.

[111] Xingfa Shen, Zhi Wang, Peng Jiang, Ruizhong Lin, and Youxian Sun. Connectivity and rssi based localization scheme for wireless sensor networks. In *Proceedings of the International Conference on Intelligent Computing (ICIC '05)*, volume 3645, pages 578–587, 2005.

[112] Ya Xu, John Heidemann, and Deborah Estrin. Geography-informed energy conservation for ad hoc routing. In *MobiCom '01: Proceedings of the 7th annual international conference on Mobile computing and networking*, pages 70–84. ACM, 2001.

[113] Yan Yu, Ramesh Govindan, and Deborah Estrin. Geographical and energy aware routing: A recursive data dissemination protocol for wireless sensor networks. Technical report, UCLA Computer Science Department Technical Report UCLA/CSD-TR-01-0023, 2001.

[114] Tian He, Chengdu Huang, Brian M. Blum, John A. Stankovic, and Tarek Abdelzaher. Range-free localization schemes for large scale sensor networks. In *MobiCom '03: Proceedings of the 9th annual international conference on Mobile computing and networking*, pages 81–95. ACM, 2003.

[115] V. Prasad and S.H. Son. Classification of analysis techniques for wireless sensor networks. In *Networked Sensing Systems, 2007. INSS '07. Fourth International Conference on*, pages 93–97, June 2007.

[116] V. Prasad, Ting Yan, P. Jayachandran, Zengzhong Li, S.H. Son, J.A. Stankovic, J. Hansson, and T. Abdelzaher. Andes: An analysis-based design tool for wireless sensor networks. In *Real-Time Systems Symposium, 2007. RTSS 2007. 28th IEEE International*, pages 203–213, Dec. 2007.

[117] Aline Baggio. Wireless sensor networks in precision agriculture. In *Proceedings of the Workshop on Real-World Wireless Sensor Networks (REALWSN'05)*, 2005.

[118] K Martinez, P Padhy, A Elsaify, G Zou, A Riddoch, J K Hart, and H L R Ong. Deploying a sensor network in an extreme environment. In *Proceedings of Sensor Networks, Ubiquitous and Trustworthy Computing*, pages 186–193, Taiwan, 2006.

[119] J Zhou and D De Roure. Coupling adaptive sampling with energy aware routing in a flood warning system. *Journal of Computer Science and Technology*, 22(1): 121–130, 2007.

[120] Kevin Sze Chiang Kuang, Ser Tong Quek, and Mohamed Maalej. Remote flood monitoring system based on plastic optical fibres and wireless motes. *Sensors and Actuators A: Physical*, 147(2):449–455, 2008.

[121] John Heidemann, Nirupama Bulusu, Jeremy Elson, Chalermek Intanagonwiwat, Kun chan Lan, Ya Xu, Wei Ye, Deborah Estrin, and Ramesh Govindan. Effects of detail in wireless network simulation. In *SCS Communication Networks and Distributed Systems Modeling and Simulation Conference*, pages 1–10, Phoenix, AZ, January 2001.

[122] M Handy and D Timmermann. Simulation of mobile wireless networks with accurate modelling of non-linear battery effects. In *Conference on Applied Simulation and Modelling*, 2003.

[123] The Network Simulator NS-2. `http://www.isi.edu/nsnam/ns/`, 2009.

[124] The Network Simulator NS-3. `http://www.nsnam.org/`, 2009.

[125] OMNeT++ Community Site. `http://www.omnetpp.org/`, 2009.

[126] Castalia: A simulator for WSNs. `http://castalia.npc.nicta.com.au/`, 2009.

[127] OPNET Technologies, Tnc. `http://www.opnet.com/`, 2009.

[128] TinyOS Community Forum. `http://tinyos.net/`, 2009.

[129] The Contiki Operating System. `http://www.sics.se/contiki/`, 2009.

[130] GloMoSim: Global Mobile Information Systems Simulation Library. `http://pcl.cs.ucla.edu/projects/glomosim/`, 2001.

[131] JSIM Official Site. `http://sites.google.com/site/jsimofficial/`, 2009.

[132] SENSE: Sensor Network Simulator and Emulator. `http://www.ita.cs.rpi.edu/sense/index.html`, 2008.

[133] Probabilistic Wireless Network Simulator. `http://www.isis.vanderbilt.edu/projects/nest/prowler`, 2008.

[134] S.G. Methley, M. Crisp, J. Newman, M. Rio, S. Bhatti, P.A. Ramsdale, and A. Atefi. Efficient mobile mesh networking: attractions, myths and techno-economic roadmap to successful commercial innovation. *New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005. 2005 First IEEE International Symposium on*, pages 361–370, Nov. 2005.

[135] Bolian Yin; Hongchi Shi; Yi Shang. Analysis of energy consumption in clustered wireless sensor networks. *Wireless Pervasive Computing, 2007. ISWPC '07. 2nd International Symposium on*, 2007.

[136] Seema Bandyopadhyay and Edward J. Coyle. An energy efficient hierarchical clustering algorithm for wireless sensor networks. In *INFOCOM*, 2003.

[137] Bassam Aoun and Raouf Boutaba. Clustering in wsn with latency and energy consumption constraints. *J. Netw. Syst. Manage.*, 14(3):415–439, 2006.

[138] A.D. Amis, R. Prakash, T.H.P. Vuong, and D.T. Huynh. Max-min d-cluster formation in wireless ad hoc networks. In *INFOCOM 2000. Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE*, volume 1, pages 32–41, 2000.

[139] Yiwei Wu, Feng Wang, My T. Thai, and Yingshu Li. Constructing k-connected m-dominating sets in wireless sensor networks. In *Military Communications Conference, 2007. MILCOM 2007. IEEE*, pages 1–7, Oct. 2007.

[140] Radhika Nagpal and Daniel Coore. An algorithm for group formation in an amorphous computer. In *Proceedings of the Tenth International Conference on Parallel and Distributed Systems (PDCS)*, 1998.

[141] Hongwei Zhang and Anish Arora. Gs3: scalable self-configuration and self-healing in wireless networks. In *PODC '02: Proceedings of the twenty-first annual symposium on Principles of distributed computing*, pages 58–67. ACM, 2002.

[142] Murat Demirbas, Anish Arora, and Vineet Mittal. Floc: A fast local clustering service for wireless sensor networks. In *Workshop on Dependability Issues in Wireless Ad Hoc Networks and Sensor Networks (DIWANS/DSN)*, 2004.

[143] Haowen Chan and Adrian Perrig. Ace: An emergent algorithm for highly uniform cluster formation. In *in Proceedings of the First European Workshop on Sensor Networks (EWSN)*, pages 154–171, 2004.

[144] Onur Arpacioglu and Zygmunt J. Haas. On the scalability and capacity of wireless networks with omnidirectional antennas. In *IPSN '04: Proceedings of the third international symposium on Information processing in sensor networks*, pages 169–177. ACM, 2004.

[145] P. Gupta and P.R. Kumar. The capacity of wireless networks. *Information Theory, IEEE Transactions on*, 46(2):388–404, Mar 2000.

[146] L.C. Zhong, J.M. Rabaey, and A. Wolisz. Does proper coding make single hop wireless sensor networks reality: the power consumption perspective. *Wireless Communications and Networking Conference, 2005 IEEE*, 2:664–669, March 2005.

[147] André B. Bondi. Characteristics of scalability and their impact on performance. In *WOSP '00: Proceedings of the 2nd international workshop on Software and performance*, pages 195–203. ACM, 2000.

[148] N Vlajic and D Xia. Wireless sensor networks: To cluster or not to cluster? In *WOWMOM '06: Proceedings of the 2006 International Symposium on on World*

of Wireless, Mobile and Multimedia Networks, pages 258–268. IEEE Computer Society, 2006.

[149] Canfeng Chen, Jian Ma, and Ke Yu. Designing energy-efficient wireless sensor networks with mobile sinks. In *WSW at Sinsys'06*, 2006.

[150] B. Haiming Yang; Sikdar. Optimal cluster head selection in the leach architecture. *Performance, Computing, and Communications Conference, 2007. IPCCC 2007. IEEE Internationa*, pages 93–100, 2007.

[151] Kaixin Xu, M. Gerla, and Sang Bae. How effective is the ieee 802.11 rts/cts handshake in ad hoc networks. In *Global Telecommunications Conference, 2002. GLOBECOM '02. IEEE*, volume 1, pages 72–76 vol.1, 2002.

[152] I. Demirkol, C. Ersoy, and F. Alagoz. Mac protocols for wireless sensor networks: a survey. *Communications Magazine, IEEE*, 44(4):115–121, April 2006.

[153] E. W. Weisstein, from MathWorld [Online]. *Birthday problem.* http://mathworld.wolfram.com/BirthdayProblem.html, 2003.

[154] Y Liu and P X Liu. A two-hop energy-efficient mesh protocol for wireless sensor networks. In *IEEE/RSJ International Conference on Intelligent Robots and Systems, 2004. (IROS 2004). Proceedings*, volume 2, pages 1786–1791, 2004.

[155] Erik Bjornemo, Mathias Johansson, and Anders Ahlen. Two hops is one too many in an energy-limited wireless sensor network. In *2007 IEEE International Conference on Acoustics, Speech, and Signal Processing*, pages 181–184, 2007.

[156] Jae-Hwan Chang and Leandros Tassiulas. Energy conserving routing in wireless ad-hoc networks. In *INFOCOM (1)*, pages 22–31, 2000.

[157] Aman Kansal and Mani B. Srivastava. An environmental energy harvesting framework for sensor networks. In *ISLPED '03: Proceedings of the 2003 international symposium on Low power electronics and design*, pages 481–486. ACM Press, 2003.

[158] Brad Karp and H T Kung. GPSR: greedy perimeter stateless routing for wireless networks. In *Mobile Computing and Networking*, pages 243–254, 2000.

[159] Brian W. Arthur. Inductive reasoning and bounded rationality. *The American Economic Review*, 84(2):406–411, 1994.

[160] U. It. Recommendation itu-r p.838-3: Specific attenuation model for rain for use in prediction methods. Recommendation ITU-R P.838-3, International Telecommunication Union, 2005.

[161] Marco Zuniga and Bhaskar Krishnamachari. Analyzing the transitional region in low power wireless links. In *In First IEEE International Conference on Sensor and Ad hoc Communications and Networks (SECON)*, pages 517–526, 2004.

[162] Karim Seada, Marco Zuniga, Ahmed Helmy, and Bhaskar Krishnamachari. Energy-efficient forwarding strategies for geographic routing in lossy wireless sensor networks. In *SenSys '04: Proceedings of the 2nd international conference on Embedded networked sensor systems*, pages 108–121. ACM, 2004.

[163] A. Alomainy, Yang Hao, and F. Pasveer. Numerical and experimental evaluation of a compact sensor antenna for healthcare devices. *Biomedical Circuits and Systems, IEEE Transactions on*, 1(4):242–249, dec. 2007.

[164] Geoff V. Merrett. *Energy- and Information- Managed Wireless Sensor Networks: Modelling and Simulation.* PhD thesis, University of Southampton, March 2009.

[165] Rahul C. Shah, Sven Wietholter, Adam Wolisz, and Jan M. Rabaey. When does opportunistic routing make sense? In *PERCOMW '05: Proceedings of the Third IEEE International Conference on Pervasive Computing and Communications Workshops*, pages 350–356. IEEE Computer Society, 2005.

[166] Katsuhiko Ogata. *Modern Control Engineering,.* Prentice Hall PTR, 4 edition, 2001.

[167] Adam Dunkels, Fredrik Österlind, and Zhitao He. An adaptive communication architecture for wireless sensor networks. In *SenSys '07: Proceedings of the 5th international conference on Embedded networked sensor systems*, pages 335–349. ACM, 2007.

[168] Carlos M. S. Figueiredo, Eduardo F. Nakamura, and Antonio A. F. Loureiro. A hybrid adaptive routing algorithm for event-driven wireless sensor networks. *Sensors*, 9(9):7287–7307, 2009.

[169] Kewei Sha and Weisong Shi. Consistency-driven data quality management of networked sensor systems. *Journal of Parallel and Distributed Computing*, 68(9): 1207–1221, 2008.

[170] Jingbo Sun. *An autonomic communication framework for wireless sensor networks.* PhD thesis, University of Western Australia, 2009.

[171] Jingbo Sun and Rachel Cardell-Oliver. An autonomic communication framework for sensor networks. In *SenSys '07: Proceedings of the 5th international conference on Embedded networked sensor systems*, pages 439–440. ACM, 2007.

[172] P. Padhy, R. Dash, K. Martinez, and N. Jennings. A utility-based adaptive sensing and multi-hop communication protocol for wireless sensor networks. *ACM Transactions on Sensor Networks*, 6(3), 2010.

[173] V Mittal, M Demirbas, and A Arora. Loci: Local clustering service for large scale wireless sensor networks. Technical report, The Ohio State University, 2003.

Simulation results

(Please see overleaf.)

PL	Beaufort		Nodes 50	100	150	200	250	300
2	2		4369.1	8499.7	12386.9	16048.6	19459.0	22716.6
		σ	12.4	16.2	42.2	88.3	59.2	64.0
	3		3112.4	6262.7	9241.9	12113.0	14892.3	17477.4
		σ	56.0	43.0	63.6	98.8	83.4	45.0
	4		1872.0	3785.9	5652.0	7464.4	9316.1	11126.3
		σ	30.9	25.8	53.3	67.5	127.4	104.3
	5		911.3	1837.4	2754.6	3670.7	4564.9	5470.9
		σ	16.5	32.7	56.4	82.7	100.4	56.8
3	2		3347.7	6526.6	9584.7	12280.7	15092.0	17759.6
		σ	313.4	160.7	223.3	233.7	294.7	215.2
	3		2333.6	4670.7	6941.1	9020.3	11063.0	13147.0
		σ	229.8	135.3	143.1	173.5	306.0	150.7
	4		1408.3	2812.1	4225.6	5463.1	6855.1	8184.6
		σ	130.9	101.9	135.5	170.4	148.7	134.1
	5		692.6	1359.3	2060.6	2695.0	3342.0	4067.4
		σ	73.8	60.4	63.2	55.7	123.7	100.2
4	2		975.7	1986.1	2967.0	3897.9	4909.1	5891.7
		σ	276.7	257.4	407.0	588.0	446.4	493.1
	3		665.3	1369.1	2067.9	2729.3	3458.3	4181.9
		σ	198.4	168.5	278.9	409.7	310.5	332.4
	4		400.6	845.3	1245.0	1644.7	2096.7	2535.6
		σ	112.9	103.9	166.8	244.2	194.9	252.2
	5		200.7	421.0	613.6	844.6	1026.7	1255.0
		σ	61.1	61.3	96.5	140.0	99.3	113.3
5	2		476.9	1001.6	1519.6	2046.6	2541.4	3119.6
		σ	162.2	188.1	277.7	443.7	388.1	301.0
	3		321.3	689.6	1054.6	1412.7	1786.7	2180.9
		σ	107.2	129.2	192.7	308.2	254.3	245.1
	4		190.0	409.1	624.1	844.7	1066.3	1308.6
		σ	66.3	74.7	104.1	174.7	165.4	121.4
	5		100.9	208.1	305.0	431.1	533.4	651.7
		σ	31.6	42.8	64.8	100.1	82.6	72.8

TABLE 1: Packet delivery with SH routing.

PL	Beaufort		Nodes 50	100	150	200	250	300
2	2		480.0	484.6	489.4	496.7	494.5	493.2
		σ	46.9	19.2	21.6	20.2	11.2	11.0
	3		478.1	484.8	488.8	497.0	493.5	492.5
		σ	45.2	20.3	21.7	20.2	10.2	9.4
	4		479.5	484.1	488.1	495.0	494.3	491.9
		σ	44.4	19.7	22.1	18.8	12.3	10.3
	5		478.5	481.8	490.0	497.6	496.6	493.1
		σ	44.9	23.3	22.0	20.9	12.9	15.1
3	2		372.6	370.9	373.3	371.7	371.9	370.4
		σ	23.2	17.3	21.9	23.2	14.0	13.6
	3		369.2	367.8	371.0	369.2	368.9	367.1
		σ	25.2	17.2	21.2	23.5	12.8	14.2
	4		368.3	367.8	369.5	368.2	367.4	367.8
		σ	21.9	13.3	23.0	20.8	13.4	13.8
	5		367.8	368.4	372.1	371.5	371.1	368.8
		σ	27.1	19.7	21.4	24.6	14.6	13.1
4	2		116.5	116.5	118.2	116.6	117.5	115.9
		σ	25.2	15.5	7.7	6.3	4.3	5.7
	3		115.2	116.6	117.3	115.4	116.9	115.2
		σ	24.6	15.6	7.9	5.6	4.3	4.8
	4		114.4	115.3	118.1	116.2	117.5	115.9
		σ	25.8	14.4	9.1	6.4	4.4	4.6
	5		116.8	115.1	118.6	117.8	117.9	118.8
		σ	24.6	14.2	7.0	5.3	5.4	5.8
5	2		57.1	57.0	58.4	58.8	59.5	59.8
		σ	12.3	8.1	6.6	6.2	5.6	4.0
	3		56.2	57.7	58.1	59.6	60.0	59.8
		σ	11.4	8.6	6.0	6.0	5.9	4.4
	4		55.3	58.0	59.0	59.9	61.0	59.7
		σ	13.4	7.6	6.4	6.3	4.4	4.6
	5		56.9	58.9	63.0	60.8	63.4	63.9
		σ	11.8	6.6	5.0	8.0	6.3	5.3

TABLE 2: Mean distance between origin and CH with SH routing.

PL	Beaufort		Nodes 50	100	150	200	250	300
2	2		0.018	0.034	0.051	0.068	0.085	0.100
		σ	0.000	0.000	0.000	0.000	0.000	0.000
	3		0.183	0.196	0.208	0.222	0.234	0.246
		σ	0.027	0.048	0.045	0.038	0.096	0.076
	4		0.261	0.272	0.282	0.292	0.301	0.311
		σ	0.033	0.065	0.041	0.031	0.035	0.064
	5		0.266	0.312	0.323	0.329	0.335	0.343
		σ	0.035	0.031	0.029	0.031	0.027	0.057
3	2		0.019	0.030	0.043	0.054	0.067	0.079
		σ	0.004	0.006	0.013	0.016	0.011	0.017
	3		0.192	0.199	0.211	0.216	0.228	0.238
		σ	0.020	0.021	0.028	0.025	0.026	0.042
	4		0.263	0.274	0.281	0.289	0.297	0.305
		σ	0.028	0.027	0.033	0.028	0.031	0.036
	5		0.219	0.288	0.314	0.325	0.333	0.338
		σ	0.027	0.034	0.036	0.043	0.034	0.036
4	2		0.034	0.041	0.045	0.048	0.052	0.056
		σ	0.021	0.018	0.017	0.019	0.026	0.041
	3		0.187	0.202	0.204	0.210	0.211	0.213
		σ	0.018	0.021	0.018	0.021	0.020	0.022
	4		0.198	0.249	0.271	0.276	0.280	0.287
		σ	0.025	0.028	0.030	0.029	0.028	0.026
	5		0.091	0.161	0.214	0.241	0.267	0.284
		σ	0.016	0.021	0.028	0.035	0.037	0.034
5	2		0.042	0.057	0.066	0.071	0.076	0.076
		σ	0.021	0.018	0.019	0.010	0.022	0.038
	3		0.158	0.185	0.201	0.208	0.211	0.216
		σ	0.021	0.020	0.020	0.020	0.020	0.013
	4		0.123	0.185	0.224	0.241	0.255	0.264
		σ	0.019	0.026	0.033	0.029	0.028	0.028
	5		0.044	0.085	0.116	0.149	0.173	0.195
		σ	0.009	0.016	0.022	0.027	0.029	0.035

TABLE 3: Collision rates with SH routing.

PL	Beaufort		Nodes 50	100	150	200	250	300
2	2		19.80	39.59	59.39	79.18	98.98	118.77
		σ	9.39	19.20	21.64	20.19	11.20	11.04
	3		151.83	173.97	195.74	217.71	239.84	261.29
		σ	45.20	20.31	21.73	20.21	10.22	9.39
	4		252.01	269.43	286.93	304.31	322.01	339.93
		σ	44.37	19.71	22.08	18.78	12.33	10.29
	5		323.92	334.56	345.09	355.57	366.02	376.75
		σ	44.88	23.31	21.99	20.91	12.94	15.13
3	2		102.66	117.64	132.79	146.65	161.93	176.92
		σ	23.25	17.31	21.90	23.22	14.05	13.55
	3		205.29	221.79	238.80	254.22	270.76	287.64
		σ	25.22	17.16	21.21	23.48	12.76	14.16
	4		283.21	296.34	309.70	321.87	335.45	348.85
		σ	21.90	13.27	22.98	20.81	13.43	13.79
	5		339.15	346.96	355.16	362.73	370.48	378.99
		σ	27.08	19.75	21.38	24.57	14.63	13.14
4	2		301.42	306.28	311.04	315.68	320.65	325.63
		σ	25.18	15.55	7.66	6.35	4.31	5.68
	3		333.45	338.67	343.78	348.79	354.18	359.62
		σ	24.59	15.60	7.87	5.65	4.33	4.79
	4		357.98	362.34	366.35	370.38	374.77	379.26
		σ	25.84	14.40	9.12	6.43	4.41	4.61
	5		375.62	378.44	381.02	383.95	386.38	389.27
		σ	24.59	14.17	6.99	5.29	5.40	5.78
5	2		347.87	350.58	353.29	356.05	358.66	361.64
		σ	12.25	8.09	6.55	6.20	5.57	4.04
	3		363.59	366.43	369.34	372.22	375.12	378.22
		σ	11.43	8.65	5.95	6.05	5.88	4.37
	4		375.54	377.90	380.26	382.69	385.06	387.65
		σ	13.40	7.58	6.42	6.33	4.41	4.63
	5		384.25	385.84	387.41	389.16	390.69	392.39
		σ	11.83	6.60	4.96	8.00	6.33	5.34

TABLE 4: Energy used by nodes with SH routing.

PL	Beaufort		Nodes 50	100	150	200	250	300
2	2		3270.7	4458.6	4462.1	4228.3	3920.0	3542.7
		σ	177.7	274.8	262.0	253.4	141.0	156.4
	3		985.7	1230.6	1438.1	1592.4	1631.1	1563.3
		σ	39.7	125.7	123.3	116.5	107.9	86.4
	4		421.7	552.7	653.9	787.1	877.1	953.3
		σ	25.0	74.3	83.5	100.2	84.4	84.8
	5		145.3	223.1	252.3	292.9	326.0	373.6
		σ	15.7	31.3	58.7	63.7	48.3	89.0
3	2		2652.9	3970.9	4263.1	4356.6	4345.1	4254.3
		σ	243.7	79.8	115.0	156.7	97.8	75.9
	3		864.1	1155.1	1413.4	1671.9	1817.3	1901.1
		σ	146.1	92.4	85.4	56.9	50.8	63.4
	4		348.1	494.7	593.7	746.6	858.7	996.1
		σ	94.1	63.4	94.0	113.1	115.3	131.9
	5		119.9	181.1	210.3	243.4	297.4	332.7
		σ	21.0	34.1	54.7	47.0	59.8	92.0
4	2		885.3	1609.4	2057.9	2459.9	2823.3	3122.4
		σ	271.1	254.0	399.9	581.6	424.9	462.2
	3		347.9	558.3	705.6	908.0	1073.6	1299.7
		σ	137.1	112.6	174.5	248.2	208.8	199.9
	4		138.6	238.4	315.4	387.6	452.3	554.4
		σ	38.4	53.2	80.6	92.1	77.8	78.9
	5		39.9	71.4	100.1	130.4	151.4	174.4
		σ	15.3	14.1	21.8	25.3	26.7	28.5
5	2		441.6	857.0	1206.9	1501.6	1762.3	1983.3
		σ	160.7	185.9	282.0	429.9	371.1	301.0
	3		204.4	388.4	552.6	689.7	799.0	946.4
		σ	70.0	87.2	127.3	175.1	180.7	138.5
	4		75.9	174.1	239.7	307.9	365.6	447.4
		σ	29.2	35.1	40.5	76.8	56.6	72.6
	5		20.4	45.1	64.1	95.1	111.0	133.9
		σ	10.2	6.8	10.0	20.3	19.7	17.4

TABLE 5: Delivery rates with GR routing.

PL	Beaufort		Nodes 50	100	150	200	250	300
2	2		433.0	647.4	993.1	1341.0	1966.3	2578.3
		σ	39.5	133.1	132.2	133.7	300.9	265.7
	3		3060.7	4568.9	5105.4	5948.1	6080.7	7208.1
		σ	675.8	687.4	688.2	644.0	372.6	489.1
	4		9744.3	10172.6	11745.1	11603.3	12539.9	12545.4
		σ	303.8	1683.3	1653.0	1165.4	1612.0	1981.9
	5		27327.9	23895.3	25951.0	23475.4	24480.3	25628.4
		σ	5172.9	6185.8	7196.2	5153.3	8764.9	5331.3
3	2		350.6	565.3	828.3	1170.3	1489.1	2141.4
		σ	67.1	71.0	138.2	213.6	172.4	245.9
	3		3608.4	5513.1	5408.1	6002.6	5916.4	6253.7
		σ	749.5	665.2	682.9	811.5	499.7	654.2
	4		12527.0	13168.9	12873.3	13828.9	13595.7	13154.7
		σ	2633.2	2952.9	2458.2	1950.3	938.7	1365.1
	5		35282.1	29774.6	31733.1	30983.7	34449.0	33351.4
		σ	10285.3	9418.6	6560.5	5120.7	5055.5	5338.8
4	2		338.9	550.3	909.4	1215.6	1459.3	1987.3
		σ	158.8	233.9	314.5	224.0	216.0	187.8
	3		3695.7	7374.7	8722.7	9968.7	9796.9	9039.0
		σ	1351.0	1121.1	1309.5	1503.8	1640.9	838.0
	4		16064.1	17967.9	15793.0	20404.1	20155.1	18671.6
		σ	6122.6	4228.9	3242.5	3423.7	3779.4	3697.7
	5		61447.1	53676.0	47540.9	47458.1	45381.4	47734.6
		σ	26589.0	23777.7	8143.2	13934.6	8710.5	12144.5
5	2		140.6	427.1	707.0	1047.0	1296.0	1534.7
		σ	51.9	133.2	412.5	277.4	505.2	369.5
	3		3074.3	4167.3	3472.0	3727.4	4962.1	4662.1
		σ	1551.8	1316.4	727.6	686.2	670.9	1183.4
	4		10134.4	11848.4	11531.3	10862.0	10332.4	10503.3
		σ	5141.0	4709.2	2595.9	3629.3	2625.7	2516.2
	5		58529.9	80759.3	52875.0	45385.4	33414.7	36095.7
		σ	4554.4	2956.0	2055.0	1225.5	790.7	939.4

TABLE 6: Mean latency with GR routing.

PL	Beaufort		Nodes 50	100	150	200	250	300
2	2		0.100	0.159	0.203	0.219	0.224	0.218
		σ	0.046	0.043	0.048	0.024	0.023	0.012
	3		0.145	0.218	0.259	0.282	0.294	0.300
		σ	0.020	0.019	0.034	0.035	0.026	0.024
	4		0.174	0.257	0.301	0.328	0.345	0.357
		σ	0.014	0.026	0.041	0.048	0.040	0.034
	5		0.173	0.263	0.315	0.348	0.368	0.386
		σ	0.016	0.024	0.056	0.051	0.038	0.035
3	2		0.100	0.148	0.190	0.207	0.220	0.223
		σ	0.019	0.043	0.040	0.047	0.026	0.019
	3		0.145	0.217	0.255	0.276	0.289	0.295
		σ	0.024	0.032	0.037	0.035	0.031	0.026
	4		0.171	0.253	0.298	0.322	0.339	0.349
		σ	0.023	0.034	0.039	0.039	0.036	0.036
	5		0.156	0.258	0.310	0.343	0.363	0.379
		σ	0.024	0.034	0.042	0.049	0.042	0.033
4	2		0.108	0.149	0.181	0.192	0.195	0.196
		σ	0.013	0.023	0.026	0.028	0.020	0.022
	3		0.125	0.198	0.246	0.267	0.275	0.277
		σ	0.011	0.030	0.029	0.029	0.027	0.027
	4		0.108	0.198	0.252	0.284	0.302	0.309
		σ	0.012	0.027	0.030	0.031	0.031	0.031
	5		0.078	0.165	0.230	0.271	0.294	0.312
		σ	0.011	0.024	0.036	0.031	0.032	0.034
5	2		0.121	0.159	0.176	0.186	0.190	0.187
		σ	0.023	0.021	0.019	0.024	0.020	0.019
	3		0.095	0.152	0.189	0.220	0.235	0.240
		σ	0.017	0.020	0.024	0.026	0.025	0.023
	4		0.056	0.118	0.169	0.209	0.232	0.250
		σ	0.011	0.020	0.025	0.024	0.026	0.025
	5		0.031	0.084	0.135	0.171	0.206	0.231
		σ	0.009	0.010	0.020	0.023	0.023	0.026

TABLE 7: Collision rate with GR routing.

PL	Beaufort		Nodes 50	100	150	200	250	300
2	2		3270.7	4458.6	4462.1	4228.3	3920.0	3542.7
		σ	177.7	274.8	262.0	253.4	141.0	156.4
	3		985.7	1230.6	1438.1	1592.4	1631.1	1563.3
		σ	39.7	125.7	123.3	116.5	107.9	86.4
	4		421.7	552.7	653.9	787.1	877.1	953.3
		σ	25.0	74.3	83.5	100.2	84.4	84.8
	5		145.3	223.1	252.3	292.9	326.0	373.6
		σ	15.7	31.3	58.7	63.7	48.3	89.0
3	2		2652.9	3970.9	4263.1	4356.6	4345.1	4254.3
		σ	243.7	79.8	115.0	156.7	97.8	75.9
	3		864.1	1155.1	1413.4	1671.9	1817.3	1901.1
		σ	146.1	92.4	85.4	56.9	50.8	63.4
	4		348.1	494.7	593.7	746.6	858.7	996.1
		σ	94.1	63.4	94.0	113.1	115.3	131.9
	5		119.9	181.1	210.3	243.4	297.4	332.7
		σ	21.0	34.1	54.7	47.0	59.8	92.0
4	2		885.3	1609.4	2057.9	2459.9	2823.3	3122.4
		σ	271.1	254.0	399.9	581.6	424.9	462.2
	3		347.9	558.3	705.6	908.0	1073.6	1299.7
		σ	137.1	112.6	174.5	248.2	208.8	199.9
	4		138.6	238.4	315.4	387.6	452.3	554.4
		σ	38.4	53.2	80.6	92.1	77.8	78.9
	5		39.9	71.4	100.1	130.4	151.4	174.4
		σ	15.3	14.1	21.8	25.3	26.7	28.5
5	2		441.6	857.0	1206.9	1501.6	1762.3	1983.3
		σ	160.7	185.9	282.0	429.9	371.1	301.0
	3		204.4	388.4	552.6	689.7	799.0	946.4
		σ	70.0	87.2	127.3	175.1	180.7	138.5
	4		75.9	174.1	239.7	307.9	365.6	447.4
		σ	29.2	35.1	40.5	76.8	56.6	72.6
	5		20.4	45.1	64.1	95.1	111.0	133.9
		σ	10.2	6.8	10.0	20.3	19.7	17.4

TABLE 8: Mean distance between origin and CH with GR routing.

PL	Beaufort		Nodes 50	100	150	200	250	300
2	2		402.7	417.7	458.6	506.4	531.9	554.3
		σ	48.8	22.7	23.3	21.1	11.8	11.6
	3		452.4	420.8	429.9	448.7	458.7	472.7
		σ	61.3	22.2	23.4	23.3	10.8	9.9
	4		523.8	523.8	515.2	523.5	522.5	528.1
		σ	39.8	24.9	22.6	21.6	11.3	9.2
	5		542.7	588.1	592.0	600.9	591.4	595.6
		σ	41.4	9.0	18.3	21.0	13.0	9.1
3	2		320.0	296.3	290.7	289.7	291.7	290.7
		σ	28.6	15.2	18.4	18.6	9.9	10.8
	3		364.8	332.0	325.0	322.3	324.1	323.4
		σ	27.1	19.6	26.7	22.8	14.4	12.6
	4		397.7	407.7	402.9	396.8	398.6	394.5
		σ	24.1	20.6	27.2	25.4	16.9	17.2
	5		440.0	444.5	461.1	465.3	468.0	465.5
		σ	24.3	14.5	17.4	18.3	12.4	15.0
4	2		114.8	114.6	116.2	114.3	114.8	113.1
		σ	26.1	15.7	8.1	6.3	4.8	5.8
	3		113.8	113.9	116.8	115.0	115.9	114.6
		σ	26.2	15.6	7.3	7.4	5.5	6.3
	4		119.3	114.7	116.7	116.6	115.9	114.4
		σ	29.2	16.8	9.1	6.2	4.2	5.7
	5		111.0	118.7	119.8	114.6	116.4	115.8
		σ	30.2	17.3	12.8	10.8	5.7	7.9
5	2		55.8	55.1	56.6	57.1	57.4	57.3
		σ	12.2	8.2	6.8	6.4	5.7	3.8
	3		55.5	55.1	56.4	57.7	57.7	57.5
		σ	11.6	7.8	7.2	6.7	6.2	4.0
	4		53.9	54.8	55.8	57.6	58.5	57.9
		σ	14.0	8.4	7.5	6.2	6.9	4.1
	5		50.6	57.8	57.9	57.3	58.7	57.1
		σ	13.4	9.3	5.8	8.4	7.9	4.6

Table 9: Delivery rates with SRD routing.

PL	Beaufort		Nodes 50	100	150	200	250	300
2	2		17.1	19.3	23.0	22.6	23.6	24.4
		σ	3.0	2.8	3.6	2.9	3.5	3.6
	3		20.0	20.7	34.7	33.3	70.0	36.4
		σ	5.6	4.2	8.3	6.1	13.2	8.1
	4		21.4	64.9	42.6	80.0	87.4	88.4
		σ	7.3	8.2	2.5	6.4	6.8	9.3
	5		18.9	25.7	83.3	96.4	114.7	130.6
		σ	0.4	13.4	16.2	10.0	17.9	9.9
3	2		13.7	15.9	14.3	16.7	14.7	14.6
		σ	0.5	3.6	1.4	5.9	1.0	0.5
	3		18.1	24.0	14.9	60.9	34.9	65.9
		σ	4.5	4.7	1.2	15.0	5.5	20.2
	4		62.6	20.6	59.7	143.3	87.4	172.7
		σ	8.1	4.5	3.6	11.2	4.3	10.5
	5		17.4	303.1	328.6	116.9	287.6	593.0
		σ	0.5	47.6	29.9	19.4	28.4	68.3
4	2		11.0	10.9	10.6	10.1	10.3	10.3
		σ	0.0	0.4	0.5	0.4	0.5	0.5
	3		11.0	11.0	18.4	30.0	31.4	19.0
		σ	0.0	0.0	4.9	12.6	12.1	4.1
	4		11.0	255.7	78.1	241.0	427.0	476.0
		σ	0.0	64.7	14.3	36.1	49.9	30.4
	5		11.0	574.1	886.6	3806.7	2301.1	3924.7
		σ	0.0	149.0	231.7	476.5	439.0	459.6
5	2		11.0	11.9	11.6	11.6	11.3	11.6
		σ	0.0	0.4	0.5	0.5	0.5	0.5
	3		11.0	11.0	11.0	11.9	53.9	28.0
		σ	0.0	0.0	0.0	0.4	6.5	4.3
	4		11.0	11.0	11.9	148.7	183.1	398.6
		σ	0.0	0.0	0.4	34.6	33.4	73.6
	5		11.0	11.0	5230.3	1778.6	380.3	114.6
		σ	0.0	0.0	1380.9	305.3	97.7	48.4

Table 10: Mean latency with SRD routing.

PL	Beaufort		Nodes 50	100	150	200	250	300
2	2		0.276	0.245	0.210	0.182	0.158	0.139
		σ	0.044	0.029	0.025	0.015	0.014	0.004
	3		0.327	0.312	0.283	0.257	0.235	0.218
		σ	0.067	0.066	0.052	0.041	0.035	0.025
	4		0.358	0.390	0.380	0.363	0.343	0.325
		σ	0.104	0.108	0.096	0.076	0.070	0.058
	5		0.310	0.393	0.427	0.439	0.440	0.437
		σ	0.144	0.158	0.157	0.146	0.131	0.119
3	2		0.262	0.254	0.227	0.201	0.178	0.158
		σ	0.090	0.060	0.048	0.034	0.032	0.013
	3		0.306	0.314	0.295	0.272	0.251	0.233
		σ	0.082	0.093	0.072	0.059	0.057	0.031
	4		0.313	0.370	0.378	0.369	0.356	0.340
		σ	0.125	0.140	0.107	0.108	0.101	0.064
	5		0.236	0.346	0.392	0.414	0.427	0.430
		σ	0.101	0.112	0.118	0.114	0.113	0.098
4	2		0.013	0.017	0.019	0.022	0.025	0.027
		σ	0.002	0.005	0.004	0.006	0.007	0.012
	3		0.017	0.025	0.030	0.034	0.037	0.040
		σ	0.002	0.003	0.004	0.007	0.007	0.009
	4		0.021	0.036	0.043	0.050	0.056	0.060
		σ	0.004	0.007	0.005	0.007	0.011	0.010
	5		0.017	0.033	0.047	0.059	0.069	0.078
		σ	0.009	0.011	0.013	0.011	0.016	0.012
5	2		0.015	0.021	0.026	0.029	0.031	0.033
		σ	0.002	0.004	0.003	0.004	0.005	0.007
	3		0.017	0.027	0.035	0.040	0.043	0.048
		σ	0.004	0.006	0.006	0.005	0.007	0.008
	4		0.017	0.028	0.037	0.048	0.054	0.059
		σ	0.005	0.004	0.006	0.006	0.007	0.009
	5		0.007	0.021	0.030	0.037	0.047	0.053
		σ	0.002	0.004	0.003	0.008	0.009	0.010

TABLE 11: Collision rate with SRD routing.

PL	Beaufort		Nodes 50	100	150	200	250	300
2	2		402.7	417.7	458.6	506.4	531.9	554.3
		σ	48.8	22.7	23.3	21.1	11.8	11.6
	3		452.4	420.8	429.9	448.7	458.7	472.7
		σ	61.3	22.2	23.4	23.3	10.8	9.9
	4		523.8	523.8	515.2	523.5	522.5	528.1
		σ	39.8	24.9	22.6	21.6	11.3	9.2
	5		542.7	588.1	592.0	600.9	591.4	595.6
		σ	41.4	9.0	18.3	21.0	13.0	9.1
3	2		320.0	296.3	290.7	289.7	291.7	290.7
		σ	28.6	15.2	18.4	18.6	9.9	10.8
	3		364.8	332.0	325.0	322.3	324.1	323.4
		σ	27.1	19.6	26.7	22.8	14.4	12.6
	4		397.7	407.7	402.9	396.8	398.6	394.5
		σ	24.1	20.6	27.2	25.4	16.9	17.2
	5		440.0	444.5	461.1	465.3	468.0	465.5
		σ	24.3	14.5	17.4	18.3	12.4	15.0
4	2		114.8	114.6	116.2	114.3	114.8	113.1
		σ	26.1	15.7	8.1	6.3	4.8	5.8
	3		113.8	113.9	116.8	115.0	115.9	114.6
		σ	26.2	15.6	7.3	7.4	5.5	6.3
	4		119.3	114.7	116.7	116.6	115.9	114.4
		σ	29.2	16.8	9.1	6.2	4.2	5.7
	5		111.0	118.7	119.8	114.6	116.4	115.8
		σ	30.2	17.3	12.8	10.8	5.7	7.9
5	2		55.8	55.1	56.6	57.1	57.4	57.3
		σ	12.2	8.2	6.8	6.4	5.7	3.8
	3		55.5	55.1	56.4	57.7	57.7	57.5
		σ	11.6	7.8	7.2	6.7	6.2	4.0
	4		53.9	54.8	55.8	57.6	58.5	57.9
		σ	14.0	8.4	7.5	6.2	6.9	4.1
	5		50.6	57.8	57.9	57.3	58.7	57.1
		σ	13.4	9.3	5.8	8.4	7.9	4.6

TABLE 12: Mean distance between origin and CH with SRD routing.

PL	Beaufort		Nodes 50	100	150	200	250	300
2	2		4320.7	5696.7	5904.6	5679.1	5238.7	4759.1
		σ	177.7	274.8	262.0	253.4	141.0	156.4
	3		2184.1	3642.1	4344.1	4616.4	4560.1	4321.1
		σ	39.7	125.7	123.3	116.5	107.9	86.4
	4		1050.0	2138.3	2964.3	3568.7	4006.1	4245.4
		σ	25.0	74.3	83.5	100.2	84.4	84.8
	5		281.1	823.9	1330.4	1823.7	2194.1	2554.3
		σ	15.7	31.3	58.7	63.7	48.3	89.0
3	2		3428.9	5101.1	5578.1	5526.4	5299.0	5036.0
		σ	243.7	79.8	115.0	156.7	97.8	75.9
	3		1644.3	2951.0	3904.6	4426.7	4719.3	4844.7
		σ	146.1	92.4	85.4	56.9	50.8	63.4
	4		693.0	1491.6	2250.0	2762.1	3255.3	3638.0
		σ	94.1	63.4	94.0	113.1	115.3	131.9
	5		209.0	491.9	860.6	1146.9	1483.3	1764.7
		σ	21.0	34.1	54.7	47.0	59.8	92.0
4	2		967.7	1970.4	2941.6	3859.7	4835.1	5803.7
		σ	271.1	254.0	399.9	581.6	424.9	462.2
	3		434.9	876.1	1316.7	1724.6	2174.6	2630.6
		σ	137.1	112.6	174.5	248.2	208.8	199.9
	4		155.1	325.4	497.0	631.7	794.9	933.3
		σ	38.4	53.2	80.6	92.1	77.8	78.9
	5		42.7	85.6	124.9	161.3	205.4	241.6
		σ	15.3	14.1	21.8	25.3	26.7	28.5
5	2		473.7	995.1	1511.0	2033.9	2513.6	3078.3
		σ	160.7	185.9	282.0	429.9	371.1	301.0
	3		206.9	443.7	670.9	906.7	1138.9	1377.6
		σ	70.0	87.2	127.3	175.1	180.7	138.5
	4		71.9	160.1	234.3	335.4	403.7	498.1
		σ	29.2	35.1	40.5	76.8	56.6	72.6
	5		23.0	43.0	67.4	88.0	100.7	134.7
		σ	10.2	6.8	10.0	20.3	19.7	17.4

TABLE 13: Delivery rates with MRD routing.

PL	Beaufort		Nodes 50	100	150	200	250	300
2	2		30.7	39.0	48.3	56.7	66.6	76.0
		σ	1.5	1.0	1.1	1.0	5.7	4.8
	3		36.9	54.0	62.7	66.1	82.9	75.6
		σ	3.3	1.6	4.5	5.5	13.3	12.8
	4		22.9	40.9	46.7	83.6	53.4	65.0
		σ	0.7	15.1	10.2	6.0	9.8	27.0
	5		19.1	39.4	27.9	68.6	102.4	107.4
		σ	0.4	4.4	4.1	8.2	11.9	7.4
3	2		24.4	30.1	35.4	38.0	40.9	45.7
		σ	0.8	1.5	2.6	3.4	2.0	1.5
	3		26.4	43.0	49.9	56.1	60.0	59.9
		σ	1.7	3.9	4.5	7.4	9.6	9.5
	4		19.7	93.1	53.0	69.9	82.7	96.0
		σ	1.0	7.7	4.1	5.2	4.0	3.4
	5		17.7	114.9	187.7	290.9	182.9	90.1
		σ	0.5	30.7	43.7	32.8	19.4	10.3
4	2		11.0	10.7	10.4	10.3	10.6	10.4
		σ	0.0	0.5	0.5	0.5	0.5	0.5
	3		11.0	10.9	14.1	30.0	31.6	19.7
		σ	0.0	0.4	8.3	5.0	4.9	1.7
	4		11.0	255.7	220.3	245.6	440.6	442.9
		σ	0.0	64.7	37.4	37.2	48.6	39.8
	5		11.0	574.1	886.6	3806.7	2301.1	3924.7
		σ	0.0	149.0	231.7	476.5	439.0	459.6
5	2		11.0	11.9	11.6	11.6	11.7	11.7
		σ	0.0	0.4	0.5	0.5	0.5	0.5
	3		11.0	11.0	11.0	11.9	53.9	28.1
		σ	0.0	0.0	0.0	0.4	6.5	4.3
	4		11.0	11.0	11.0	148.7	183.1	398.6
		σ	0.0	0.0	0.0	34.6	33.4	73.6
	5		11.0	11.0	12.6	1778.6	380.3	114.6
		σ	0.0	0.0	4.2	305.3	97.7	129.1

TABLE 14: Mean latency with MRD routing.

PL	Beaufort		Nodes 50	100	150	200	250	300
2	2		0.281	0.246	0.210	0.181	0.158	0.139
		σ	0.064	0.053	0.034	0.021	0.018	0.024
	3		0.320	0.312	0.286	0.261	0.239	0.222
		σ	0.101	0.066	0.075	0.060	0.094	0.077
	4		0.344	0.381	0.376	0.363	0.344	0.326
		σ	0.133	0.116	0.140	0.125	0.095	0.072
	5		0.303	0.384	0.418	0.431	0.436	0.433
		σ	0.141	0.136	0.157	0.141	0.129	0.179
3	2		0.271	0.257	0.227	0.201	0.178	0.158
		σ	0.159	0.134	0.182	0.190	0.137	0.087
	3		0.297	0.313	0.296	0.276	0.256	0.237
		σ	0.163	0.176	0.152	0.099	0.106	0.146
	4		0.302	0.361	0.373	0.366	0.356	0.341
		σ	0.182	0.190	0.207	0.182	0.152	0.173
	5		0.233	0.339	0.383	0.406	0.421	0.425
		σ	0.195	0.218	0.181	0.169	0.135	0.100
4	2		0.013	0.017	0.019	0.022	0.024	0.027
		σ	0.001	0.003	0.004	0.005	0.006	0.008
	3		0.017	0.025	0.030	0.034	0.037	0.039
		σ	0.001	0.002	0.003	0.005	0.006	0.009
	4		0.021	0.036	0.042	0.051	0.056	0.061
		σ	0.003	0.005	0.003	0.006	0.009	0.008
	5		0.017	0.033	0.047	0.059	0.069	0.077
		σ	0.007	0.009	0.011	0.009	0.012	0.010
5	2		0.016	0.021	0.026	0.028	0.031	0.032
		σ	0.001	0.002	0.002	0.002	0.003	0.005
	3		0.017	0.027	0.035	0.040	0.043	0.048
		σ	0.003	0.003	0.003	0.003	0.004	0.004
	4		0.017	0.028	0.037	0.049	0.054	0.059
		σ	0.003	0.007	0.011	0.004	0.004	0.009
	5		0.007	0.021	0.030	0.037	0.047	0.053
		σ	0.002	0.004	0.004	0.003	0.003	0.004

TABLE 15: Collision rate with MRD routing.

PL	Beaufort		Nodes 50	100	150	200	250	300
2	2		4320.7	5696.7	5904.6	5679.1	5238.7	4759.1
		σ	177.7	274.8	262.0	253.4	141.0	156.4
	3		2184.1	3642.1	4344.1	4616.4	4560.1	4321.1
		σ	39.7	125.7	123.3	116.5	107.9	86.4
	4		1050.0	2138.3	2964.3	3568.7	4006.1	4245.4
		σ	25.0	74.3	83.5	100.2	84.4	84.8
	5		281.1	823.9	1330.4	1823.7	2194.1	2554.3
		σ	15.7	31.3	58.7	63.7	48.3	89.0
3	2		3428.9	5101.1	5578.1	5526.4	5299.0	5036.0
		σ	243.7	79.8	115.0	156.7	97.8	75.9
	3		1644.3	2951.0	3904.6	4426.7	4719.3	4844.7
		σ	146.1	92.4	85.4	56.9	50.8	63.4
	4		693.0	1491.6	2250.0	2762.1	3255.3	3638.0
		σ	94.1	63.4	94.0	113.1	115.3	131.9
	5		209.0	491.9	860.6	1146.9	1483.3	1764.7
		σ	21.0	34.1	54.7	47.0	59.8	92.0
4	2		967.7	1970.4	2941.6	3859.7	4835.1	5803.7
		σ	271.1	254.0	399.9	581.6	424.9	462.2
	3		434.9	876.1	1316.7	1724.6	2174.6	2630.6
		σ	137.1	112.6	174.5	248.2	208.8	199.9
	4		155.1	325.4	497.0	631.7	794.9	933.3
		σ	38.4	53.2	80.6	92.1	77.8	78.9
	5		42.7	85.6	124.9	161.3	205.4	241.6
		σ	15.3	14.1	21.8	25.3	26.7	28.5
5	2		473.7	995.1	1511.0	2033.9	2513.6	3078.3
		σ	160.7	185.9	282.0	429.9	371.1	301.0
	3		206.9	443.7	670.9	906.7	1138.9	1377.6
		σ	70.0	87.2	127.3	175.1	180.7	138.5
	4		71.9	160.1	234.3	335.4	403.7	498.1
		σ	29.2	35.1	40.5	76.8	56.6	72.6
	5		23.0	43.0	67.4	88.0	100.7	134.7
		σ	10.2	6.8	10.0	20.3	19.7	17.4

TABLE 16: Mean distance between origin and CH with MRD routing.

PL	Beaufort		Nodes 50	100	150	200	250	300
2	2		3110.6	4142.9	4485.4	4221.1	3989.7	3675.3
		σ	260.4	405.5	537.8	525.8	396.7	289.5
	3		1230.3	1270.3	1210.0	1100.9	948.9	844.4
		σ	89.6	144.4	83.1	89.2	142.5	65.7
	4		439.0	471.3	461.1	419.3	374.4	355.6
		σ	21.8	32.5	71.0	59.4	95.0	47.6
	5		141.6	168.4	157.9	142.1	144.7	143.6
		σ	16.1	20.2	10.3	16.6	14.5	12.1
3	2		4031.7	5108.1	4937.1	4547.7	4025.9	3768.3
		σ	471.6	497.4	392.3	500.5	279.8	256.4
	3		1212.7	1418.1	1351.9	1369.7	1176.3	1075.1
		σ	104.1	188.2	253.1	60.4	503.3	244.3
	4		419.3	478.4	494.4	461.1	445.4	447.7
		σ	31.9	45.3	43.0	198.4	141.2	56.3
	5		130.1	165.6	165.4	165.9	164.6	163.6
		σ	11.0	21.7	23.3	15.0	8.5	12.8
4	2		1226.1	2344.3	2675.9	2777.0	2743.9	2858.1
		σ	385.6	563.2	490.7	352.3	320.6	326.2
	3		440.6	737.1	902.6	974.1	1145.6	1326.1
		σ	127.6	144.9	132.7	146.9	172.4	169.2
	4		146.9	292.7	358.4	365.9	420.1	489.9
		σ	43.6	59.2	53.0	102.8	89.8	56.0
	5		40.7	76.4	121.4	129.7	140.0	140.1
		σ	13.1	28.6	19.4	19.8	17.0	17.4
5	2		480.9	1161.1	1657.7	1920.4	2064.7	2230.1
		σ	119.7	308.0	216.0	164.1	242.9	291.7
	3		220.0	491.9	805.9	905.9	1048.9	1185.0
		σ	64.1	135.9	125.2	146.9	171.4	133.7
	4		84.0	186.7	298.6	361.6	440.6	555.3
		σ	22.1	74.1	72.5	98.4	88.3	98.6
	5		21.9	53.3	82.4	99.6	130.1	141.9
		σ	8.5	20.1	19.0	24.5	18.6	25.9

Table 17: Delivery rates with GR opportunistic routing.

PL	Beaufort		Nodes 50	100	150	200	250	300
2	2		391.7	624.7	917.1	1318.3	1782.6	2369.0
		σ	106.8	56.3	165.2	363.1	450.8	277.3
	3		1565.7	2119.0	2988.3	2899.0	3844.0	4406.1
		σ	278.9	236.8	279.8	388.7	306.9	603.7
	4		3012.1	2810.3	3211.7	3795.9	3690.9	4233.7
		σ	601.2	458.4	582.6	604.9	604.4	768.1
	5		4657.3	3209.7	4025.0	3833.3	4191.0	4539.3
		σ	759.2	1160.5	496.3	928.5	897.8	1457.4
3	2		274.9	467.7	777.4	988.0	1408.3	1912.0
		σ	62.5	72.1	175.0	223.7	286.0	161.1
	3		1578.1	1981.0	2204.3	2705.7	2927.7	3099.6
		σ	169.1	381.3	381.9	318.1	608.5	250.1
	4		3310.4	3083.7	3235.1	2712.3	3654.9	4003.9
		σ	347.4	569.5	668.1	597.2	545.0	599.3
	5		6065.9	4593.4	3567.9	3980.6	3586.0	4476.3
		σ	1025.2	961.8	649.0	681.5	792.3	1043.8
4	2		242.3	444.4	736.3	1033.4	1414.6	1835.4
		σ	119.6	89.5	162.0	346.3	339.1	321.3
	3		2856.3	2764.3	2944.3	3122.4	3186.0	3016.4
		σ	639.3	431.6	428.4	369.2	817.9	430.9
	4		9139.4	4907.0	4110.7	4076.1	3762.4	3383.7
		σ	2404.8	843.8	900.5	580.7	549.9	565.6
	5		25472.4	12469.0	6560.4	5631.0	5092.6	5429.0
		σ	9778.9	5233.6	2189.2	1178.6	1262.9	1069.6
5	2		167.4	320.1	622.0	901.0	1267.1	1486.0
		σ	66.8	138.7	166.5	380.5	367.5	394.1
	3		2098.6	2599.4	2398.3	2394.7	2365.6	2470.6
		σ	1862.4	991.4	425.9	326.6	303.3	324.5
	4		4738.7	8024.4	5785.7	4699.4	4160.9	3437.4
		σ	3992.6	4321.6	2345.2	1258.1	844.4	738.3
	5		28299.1	22049.6	14128.1	8481.7	6635.0	5918.0
		σ	2125.9	8307.4	5654.6	1615.8	1993.7	1187.9

Table 18: Mean latency with GR opportunistic routing.

PL	Beaufort		Nodes 50	100	150	200	250	300
2	2		0.099	0.207	0.293	0.372	0.443	0.507
		σ	0.030	0.037	0.045	0.075	0.091	0.111
	3		0.372	0.484	0.570	0.630	0.678	0.712
		σ	0.075	0.061	0.089	0.142	0.132	0.139
	4		0.478	0.596	0.657	0.705	0.741	0.768
		σ	0.074	0.124	0.127	0.142	0.149	0.154
	5		0.559	0.678	0.740	0.773	0.799	0.820
		σ	0.120	0.127	0.131	0.152	0.149	0.161
3	2		0.174	0.286	0.384	0.447	0.512	0.555
		σ	0.074	0.062	0.051	0.082	0.097	0.135
	3		0.396	0.524	0.604	0.658	0.702	0.738
		σ	0.066	0.069	0.125	0.087	0.141	0.147
	4		0.476	0.621	0.689	0.728	0.761	0.788
		σ	0.139	0.102	0.138	0.146	0.152	0.166
	5		0.495	0.667	0.740	0.780	0.807	0.829
		σ	0.095	0.153	0.139	0.145	0.163	0.154
4	2		0.288	0.433	0.517	0.578	0.621	0.647
		σ	0.069	0.092	0.093	0.096	0.125	0.119
	3		0.294	0.470	0.567	0.631	0.665	0.696
		σ	0.061	0.117	0.131	0.122	0.119	0.132
	4		0.283	0.456	0.553	0.621	0.670	0.709
		σ	0.073	0.108	0.122	0.125	0.126	0.149
	5		0.200	0.399	0.517	0.580	0.633	0.677
		σ	0.045	0.097	0.143	0.155	0.147	0.157
5	2		0.172	0.317	0.417	0.472	0.523	0.566
		σ	0.061	0.061	0.098	0.117	0.122	0.123
	3		0.091	0.302	0.402	0.472	0.517	0.578
		σ	0.019	0.072	0.119	0.123	0.131	0.131
	4		0.068	0.282	0.380	0.454	0.506	0.564
		σ	0.016	0.077	0.094	0.105	0.134	0.129
	5		0.043	0.196	0.286	0.383	0.447	0.510
		σ	0.010	0.061	0.066	0.123	0.107	0.111

TABLE 19: Collision rate with GR opportunistic routing.

PL	Beaufort		Nodes 50	100	150	200	250	300
2	2		479.6	458.0	450.7	439.9	433.4	422.1
		σ	29.1	29.9	21.1	17.6	18.5	13.6
	3		505.7	464.9	440.9	431.4	408.2	393.7
		σ	38.3	27.2	17.5	18.8	13.3	18.8
	4		490.6	455.1	419.0	408.6	391.0	385.1
		σ	29.0	30.4	35.5	26.7	19.2	22.3
	5		494.8	469.0	427.9	401.5	388.1	386.0
		σ	45.5	56.7	24.7	28.5	38.6	18.5
3	2		529.8	491.8	457.7	433.5	398.6	381.4
		σ	27.5	25.6	23.5	19.3	21.9	13.2
	3		445.4	424.7	409.5	398.6	389.4	368.4
		σ	30.9	25.5	27.6	19.8	25.8	22.5
	4		411.6	379.0	360.4	376.4	333.5	319.1
		σ	34.3	40.5	24.7	61.5	22.7	20.6
	5		390.6	378.9	346.0	351.2	336.2	318.3
		σ	34.6	44.9	47.9	34.8	34.8	39.3
4	2		171.6	181.2	169.6	163.1	155.6	150.5
		σ	25.6	19.3	15.4	14.6	11.2	10.6
	3		143.5	144.8	132.1	125.4	128.6	130.2
		σ	25.2	23.6	14.7	12.3	10.0	8.3
	4		130.1	133.6	120.3	114.5	107.1	105.5
		σ	25.8	22.8	17.8	17.1	12.9	8.4
	5		131.1	136.5	127.2	122.9	121.8	111.0
		σ	32.0	20.7	14.2	19.0	17.4	11.1
5	2		63.9	88.4	87.6	87.8	81.9	78.6
		σ	27.1	19.7	8.9	8.8	9.4	10.3
	3		63.8	77.0	74.1	71.9	67.3	64.1
		σ	24.3	16.8	9.9	9.2	9.7	7.8
	4		61.6	75.0	67.8	68.7	64.8	63.6
		σ	22.1	13.1	11.6	9.7	10.5	6.7
	5		62.1	71.8	66.4	67.5	65.8	63.4
		σ	22.4	15.8	11.1	10.0	12.3	3.7

TABLE 20: Mean distance between origin and CH with GR opportunistic routing.

PL	Beaufort		Nodes 50	100	150	200	250	300
2	2		0.594	0.642	0.826	0.870	0.901	0.921
		σ	0.115	0.304	0.260	0.281	0.284	0.286
	3		0.453	0.590	0.675	0.727	0.764	0.793
		σ	0.266	0.344	0.341	0.312	0.311	0.283
	4		0.459	0.570	0.627	0.668	0.703	0.734
		σ	0.091	0.307	0.245	0.238	0.279	0.240
	5		0.513	0.646	0.731	0.765	0.782	0.795
		σ	0.157	0.258	0.283	0.258	0.251	0.264
3	2		0.488	0.664	0.754	0.805	0.841	0.868
		σ	0.268	0.287	0.294	0.294	0.265	0.280
	3		0.450	0.577	0.654	0.703	0.744	0.775
		σ	0.146	0.144	0.210	0.207	0.230	0.236
	4		0.476	0.615	0.678	0.716	0.739	0.761
		σ	0.153	0.135	0.217	0.162	0.167	0.197
	5		0.464	0.641	0.719	0.780	0.806	0.820
		σ	0.191	0.206	0.219	0.239	0.263	0.232
4	2		0.005	0.053	0.128	0.235	0.318	0.403
		σ	0.005	0.048	0.114	0.128	0.161	0.203
	3		0.001	0.039	0.125	0.232	0.313	0.379
		σ	0.001	0.048	0.130	0.156	0.176	0.196
	4		0.005	0.019	0.067	0.166	0.156	0.201
		σ	0.001	0.005	0.034	0.062	0.076	0.060
	5		0.001	0.001	0.015	0.094	0.003	0.117
		σ	0.001	0.001	0.006	0.023	0.001	0.022
5	2		0.002	0.005	0.026	0.046	0.081	0.171
		σ	0.001	0.001	0.011	0.027	0.022	0.042
	3		0.001	0.005	0.015	0.020	0.083	0.123
		σ	0.001	0.003	0.004	0.007	0.021	0.042
	4		0.000	0.001	0.004	0.022	0.024	0.100
		σ	0.000	0.001	0.001	0.006	0.006	0.035
	5		0.000	0.000	0.000	0.001	0.001	0.002
		σ	0.000	0.000	0.000	0.001	0.001	0.001

TABLE 21: Delivery rates with SRD opportunistic routing.

PL	Beaufort		Nodes 50	100	150	200	250	300
2	2		394.6	395.4	428.8	463.6	491.6	500.6
		σ	37.8	32.6	20.1	17.3	21.3	21.7
	3		549.1	521.4	512.6	515.1	517.1	522.7
		σ	27.5	29.9	24.5	16.7	19.4	16.3
	4		596.2	595.7	593.8	592.3	587.6	585.7
		σ	27.6	25.2	18.6	14.8	15.2	16.9
	5		631.6	623.3	620.5	620.5	622.9	626.6
		σ	37.0	35.9	20.1	13.5	11.2	13.7
3	2		461.6	429.6	411.6	414.5	405.7	407.6
		σ	37.8	34.1	23.7	24.2	20.6	16.1
	3		492.1	486.0	472.3	467.8	457.6	450.3
		σ	30.8	29.5	22.9	17.5	18.5	20.3
	4		503.1	520.7	511.5	503.6	500.4	494.3
		σ	27.5	21.8	19.4	15.8	16.6	14.7
	5		531.9	549.5	552.6	545.9	537.6	532.6
		σ	27.5	28.6	19.2	16.4	19.6	15.9
4	2		110.7	128.2	128.0	137.3	139.7	146.1
		σ	28.8	21.8	22.4	16.7	15.0	16.5
	3		110.7	125.1	129.4	137.5	140.0	145.0
		σ	27.7	22.3	21.4	14.8	14.5	16.2
	4		109.9	122.8	127.1	134.1	132.6	133.2
		σ	29.1	21.1	24.2	28.8	13.4	7.0
	5		113.6	124.7	119.6	130.7	116.6	127.0
		σ	30.2	22.5	20.4	32.1	13.7	30.8
5	2		57.9	62.5	58.8	61.4	61.5	66.8
		σ	22.2	15.0	8.6	12.6	10.6	11.4
	3		58.1	63.0	57.9	59.7	61.9	64.0
		σ	22.8	14.5	8.6	11.7	9.1	8.0
	4		58.2	63.5	57.3	58.5	58.4	63.5
		σ	22.9	14.0	9.4	7.9	8.5	11.0
	5		55.1	63.3	59.4	58.2	56.5	56.4
		σ	24.7	14.2	5.9	11.7	11.5	8.2

TABLE 22: Mean distance between origin and CH with SRD opportunistic routing.

PL	Beaufort		Nodes 50	100	150	200	250	300
2	2		4266.3	5870.3	6149.4	5875.6	5211.0	4357.1
		σ	156.5	263.7	237.6	254.2	352.0	243.2
	3		4330.7	6543.3	7045.4	6899.0	6592.3	5580.7
		σ	78.4	138.7	198.2	226.7	332.2	1421.9
	4		2187.1	4305.6	6065.0	6925.0	7235.6	7373.7
		σ	78.1	194.0	102.4	180.7	170.9	282.2
	5		1234.1	2167.0	2671.0	3262.7	3782.3	4466.4
		σ	66.0	115.5	134.9	84.2	446.1	398.3
3	2		5507.1	7381.6	7704.7	7360.1	6238.4	6102.6
		σ	413.3	286.8	275.7	117.7	1739.9	180.7
	3		3651.3	5995.0	7221.7	7884.1	7986.9	7814.7
		σ	207.2	373.0	398.2	241.1	157.4	188.3
	4		1714.4	3436.7	4715.4	5781.6	6520.9	7239.3
		σ	126.9	264.0	240.0	291.3	270.9	283.0
	5		807.3	1752.6	2287.1	2811.7	2896.7	3699.7
		σ	101.9	132.7	171.1	189.7	1190.3	177.4
4	2		862.4	2028.1	3130.6	4086.7	5254.3	6412.4
		σ	296.8	416.2	611.8	614.2	781.9	705.7
	3		393.9	906.4	1418.9	1872.6	2420.3	2932.0
		σ	127.6	195.9	263.7	266.5	334.4	422.5
	4		144.7	323.3	521.6	681.3	858.1	1105.4
		σ	47.5	68.1	119.7	121.0	103.5	141.7
	5		36.9	83.9	133.4	151.3	198.0	267.9
		σ	16.6	18.1	27.5	22.5	37.9	51.8
5	2		449.0	926.7	1527.4	1969.6	2625.4	3343.6
		σ	104.2	250.3	330.4	391.2	546.6	523.3
	3		196.7	405.0	680.6	875.7	1217.9	1534.1
		σ	45.8	120.2	144.0	171.2	269.8	194.3
	4		69.3	151.4	243.1	299.6	452.9	593.9
		σ	20.1	43.2	58.3	69.1	162.1	69.7
	5		22.7	42.6	61.9	74.9	99.9	125.9
		σ	4.9	16.2	10.8	18.5	24.3	17.5

Table 23: Delivery rates with MRD opportunistic routing.

PL	Beaufort		Nodes 50	100	150	200	250	300
2	2		469.2	477.3	494.9	518.1	533.7	537.5
		σ	29.2	28.8	17.8	16.3	17.7	20.2
	3		583.0	574.2	569.3	570.3	576.1	581.8
		σ	28.8	31.4	20.1	9.2	15.0	14.9
	4		609.7	604.4	610.7	612.4	612.0	611.9
		σ	32.1	26.1	17.7	12.7	16.9	17.4
	5		636.8	631.8	630.2	630.9	633.6	634.9
		σ	29.3	31.0	15.2	13.3	12.1	15.5
3	2		541.6	503.8	483.0	480.9	470.7	462.4
		σ	33.2	26.3	21.1	18.4	18.0	12.6
	3		523.3	518.0	516.0	516.7	508.4	507.4
		σ	26.3	22.4	19.6	15.1	13.7	10.2
	4		534.6	534.5	529.5	525.9	521.6	520.8
		σ	25.0	24.3	18.2	14.6	16.5	13.8
	5		563.7	566.8	562.8	567.5	560.0	549.8
		σ	26.8	32.7	23.6	16.1	14.0	21.3
4	2		110.7	130.8	138.3	152.1	158.8	169.3
		σ	28.9	24.2	23.0	22.4	25.8	15.8
	3		110.7	132.2	139.6	162.3	171.1	172.7
		σ	27.7	24.0	15.9	28.2	21.7	25.7
	4		109.2	126.8	130.3	151.4	157.4	181.8
		σ	28.8	28.3	31.8	47.4	37.9	44.3
	5		113.6	124.7	121.9	125.5	116.6	145.7
		σ	30.2	22.5	24.9	19.5	13.7	55.0
5	2		57.9	62.5	59.9	62.4	64.7	71.6
		σ	22.2	15.0	10.2	12.7	11.1	13.6
	3		58.1	63.0	58.7	60.0	70.8	74.7
		σ	22.8	14.5	8.3	12.4	10.5	11.1
	4		58.2	63.5	57.6	58.6	70.2	84.0
		σ	22.9	14.0	9.5	7.8	24.5	38.9
	5		55.1	63.3	59.4	58.2	56.5	56.4
		σ	24.7	14.2	5.9	11.7	11.5	8.2

Table 24: Mean distance between origin and CH with MRD opportunistic routing.

Selected publications

Barbosa, P., White, N.M., Harris, N.R. Medium Access Control in Large Scale Clusters for Wireless Sensor Networks. *IEEE 23rd International Conference on Advanced Information Networking and Applications AINA 2009*, Bradford, UK, 26-29 May 2009.

Barbosa, P., White, N.M., Harris, N.R. Wireless Sensor Networks for Localised Maritime Monitoring. *IEEE 22nd International Conference on Advanced Information Networking and Applications AINA 2008*, Okinawa, Japan, 25-28 March 2008.

Barbosa, P., White, N.M., Harris, N.R. Wireless Sensor Networks for Maritime Deployment: Modeling and Simulation. *IEEE 15th Mediterranean Electrotechnical Conference Melecon 2010*, Valletta, Malta, 25-28 April 2010.